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# Productivity, Costs, and Best Management Practices for Major Timber Harvesting Frameworks in Maine

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**PRODUCTIVITY, COSTS, AND BEST MANAGEMENT PRACTICES FOR MAJOR  
TIMBER HARVESTING FRAMEWORKS IN MAINE**

By

Harikrishnan Soman

B.Sc. (Hons.) Kerala Agricultural University, Kerala (India), 2014

A THESIS

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

(in Forest Resources)

The Graduate School

The University of Maine

May 2019

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An Abstract of the Thesis Presented

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Though the timber harvesting industry in Maine is over two centuries old, the state has more forest cover than a century ago. Currently, some of the crucial challenges faced by the forest management industry in Maine and elsewhere in the northeastern US are increasing costs of forest operations, diminishing monetary returns and falling markets.

The major goal of this study was to evaluate the production economics of timber harvesting frameworks under different silvicultural prescriptions common to the region. Two field-based studies were conducted at two different locations in Maine, US. The first field study (Study I) was conducted in Grand Falls Township, central Maine during July-August 2017. The primary objective of this study was to estimate and compare the operational productivity and costs of harvesting under different silvicultural prescriptions, that included two variants each of partial harvest (PH) and clearcut (CC), using a whole-tree (WT) harvest method. Other objectives included estimating the costs associated with best management practices (BMPs) implementation and scrutinization of the

important factors influencing production economics of harvesting. The second part of the field study (Study II) was conducted in the Penobscot Experimental Forest, central Maine during February-March 2018. As the majority of the stand establishment in Maine is dependent on natural regeneration for continuous replenishment of stands, the objectives of this study were to evaluate and compare production economics of a hybrid tree-length (Hyb TL) harvesting method to a conventional WT method in a strip CC. The study also focused on comparing at-stump and at-landing processing of logs along with estimation of BMP implementation costs.

Detailed time-motion studies were conducted, and machine rate calculations were done for productivity and cost estimation. Variables collected included stand features, delay free cycle (DFC) times of machines, and predictor variables such as distance travelled, and number and size of logs handled per cycle. Results from Study I followed an expected trend of PH operations being costlier than CC (nearly 54% higher). For Study II, Hyb TL method was found to be comparatively less costly than WT harvesting (8% less). At-stump and at-landing processing costs were comparable (\$2.66 m<sup>-3</sup> and \$2.73 m<sup>-3</sup>). Trends in costs were similar for both studies with extraction being the most expensive component (50 to 70% of total costs). BMP costs quantified for both studies were in the range of \$10 and \$52 PMH<sup>-1</sup> or \$1.0 to \$3.7 m<sup>-3</sup> of wood harvested. Results showed that BMPs can be coupled to industrial harvesting operations without considerably affecting the operational costs.

Inferences from this study can help operations managers, researchers, and landowners to better understand the impacts of alternative harvesting scenarios in the region and will help them in pinpointing areas that need improvement.

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## **LIST OF ABBREVIATIONS**

BA – Basal Area  
BAF – Basal Area Factor  
BMP – Best Management Practice  
CC – Clearcut  
CTL – Cut-to-length  
DBH – Diameter at Breast Height  
DFC – Delay Free Cycle time  
GIS – Geographic Information System/Studies  
ha – Hectare  
Hyb TL – Hybrid tree-length  
L – Liter  
m – meter  
N/A – Not Applicable  
PH – Partial Harvest  
PMH – Productive Machine Hour  
sec – Seconds  
SMH – Scheduled Machine Hour  
TL – Tree-Length  
US – United States of America  
US \$ – United States Dollar  
WT – Whole-tree

## **CHAPTER 1:**

### **INTRODUCTION**

#### **1.1. Forestry and Forest Products Industry in Maine**

Maine has the highest percentage of the total state area under forest cover (89%) amongst the states in the US. Around 7,137,870 ha of land in the state is forested, out of which almost 97% is regarded as potential timberland (NESFA 2013). The major share of Maine's forest ownership (more than 90%) is under the private sector (either companies or families). The remaining is owned by local communities, state, and federal governments. Timber harvesting and related industries are vital for Maine's economy as they offered about 33,538 jobs contributing around \$8.5 billion to the economy (MFPC 2016).

The economic aspect of forest management is one of the primary concerns for industrial timberlands. The timber harvesting industry in Maine is one of the largest in the New England region, and accounts for more than 50% of all harvested wood products in the region (Leon & Benjamin 2013). However, after six recent mill shutdowns within the past seven years, the setbacks to the timber harvesting industry have intensified (Koirala et al. 2017; Kingsley 2019).

The economics of timber harvesting are commonly expressed in terms of productivity and operational costs. Information on the productivity and costs of timber harvesting is a key component in the consideration of management plans for the utilization and regeneration of forests (Behjou et al. 2008). Productivity of a harvesting operation is defined as the volume or mass of timber handled per productive machine hour (PMH), whereas cost of harvesting is usually evaluated by adding up the cost of individual operational phases (an operational phase is defined as a part of the operation that brings about a change in the form or location of the logs).

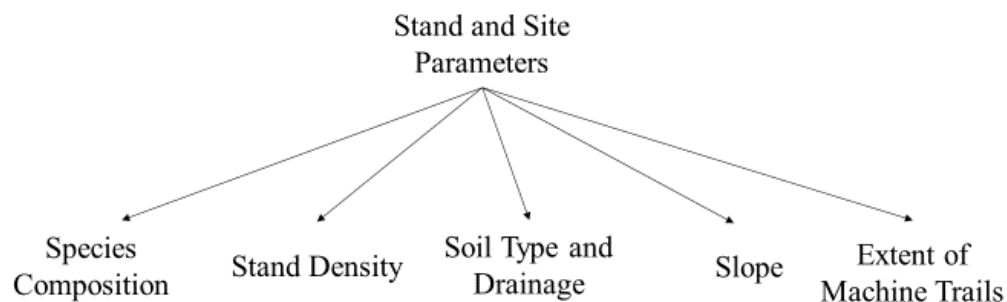


Productivity and cost of harvesting are inversely related i.e., as harvesting productivity increases, cost decreases. A variety of factors are expected to influence productivity. A thorough understanding of these factors is essential for effective planning and execution of economically efficient and environmentally sustainable timber harvesting operations.

Some of the most influential factors affecting harvesting productivity of the region are:

## 1.2. Stand and Site Parameters

Stand and site parameters are factors primarily associated with the land base of the harvest unit for a typical ground-based system (Figure 1.1).



**Figure 1.1.** Stand and site variables influencing the productivity and cost of a harvesting operation.

*Species composition* influences factors like growth rates, tree form, silvics, and stand regeneration strategies which in turn impact the production economics (Hiesl 2013). Stem size and wood properties that vary between species have been found to influence the time needed for different operational phases. For example, more time required for felling and processing hardwoods compared to softwoods reduces productivity. Mixedwood stands (composed of softwoods and hardwoods in mixture) often have a wide range stem sizes (in terms of diameter

at breast height (DBH) or volume) and stand densities (basal area or trees per unit area). Both stands studied as a part of this research were mixedwood.

*Stand density*, in terms of basal area  $\text{ha}^{-1}$  and trees  $\text{ha}^{-1}$ , can influence the productivity of harvesting equipment (Hiesl 2013). Average DBH and basal area of the stand have been found to significantly influence productivity (Lanford & Stokes 1996; Kluender et al. 1998; Wang et al. 2004; Li et al. 2006). Contrary to this, other studies conducted in Maine have found that cycle time, which influences productivity, was not dependent on DBH within individual species for a feller-buncher (Hiesl 2013).

*Soil type* and *drainage* of the site are major factors usually considered while designing harvest layouts. Steady soil types enable faster movement of machines through the trails, whereas unstable soils with poor drainage can cause delays in machine movement thereby reducing productivity (Contreras et al. 2016). A decrease in forwarder productivity was also reported due to lower bearing capacity of the soil (Poršinsky et al. 2011). As extraction of wood is the costliest component of harvest operations (Kizha & Han 2016; Soman et al. 2019), skid trails are conventionally laid out to minimize moving distances to increase the extraction productivity (Greulich 2003). Additionally, soil type and drainage should be considered during skid trail design in order to reduce safety hazards and enhance extraction productivity (Contreras et al. 2016; Soman et al. 2019). Harvesting practices that exclude susceptible soil types from the operational path may lead to an increase in the total harvesting costs (Han 2007).

*Slope* can significantly affect the accessibility of a machine in the stand. Steeper terrain increases in-woods movement time (Spinelli & Magagnotti 2010), thereby decreasing productivity compared to gentle slopes (Mousavi 2012). This has been identified as one of the primary factors

affecting extraction productivity (Behjou et al. 2008). Even though exact comparisons cannot be made due to variation in site conditions, operational constraints, machines used and difference in research timeframe, higher productivity of extraction was reported for stands with slopes ranging from 2–14% ( $47.5 \text{ m}^3 \text{ PMH}^{-1}$ ) compared to stands with 30% slope ( $8.2 \text{ m}^3 \text{ PMH}^{-1}$ ) (Wang et al. 2004; Hiesl 2013). On another note, most of the ground-based machines are not designed to operate in slopes more than 40%. Direction of loaded extraction distance also influences productivity. Naghdi (1996) evaluated the productivity of downhill extraction to be 16% higher than that of uphill extraction.

*Extent of machine trails* is inversely related to total productivity (Han et al. 2004; Mousavi 2012; Kizha & Han 2016). Sabo & Poršinsky (2005) reported productivity of  $12 \text{ m}^3 \text{ PMH}^{-1}$  for an average skidding distance of 250 m. Extraction productivity decreased by  $3 \text{ m}^3 \text{ PMH}^{-1}$  for a 100-m increase in average skidding distance and extraction cost increased by about 70% for a 350-m increase in skidding distance. Furthermore, this factor influences the equipment selection and long skid trails can be a bottleneck for the productivity of the processor.

### **1.3. Silvicultural Prescription**

Silvicultural prescription for a stand is primarily determined by the objectives of stand management, market requirements, desired post-harvest stand conditions, and regulations that control harvesting (Davis 1966; Nyland 2016) and is important in deciding the quality and quantity of wood to be harvested, and future regeneration of the stand. Nonetheless, future regeneration techniques also decide the silvicultural prescriptions intended to be adopted. Natural regeneration of a stand can be achieved by both CC and PH. In CC, natural regeneration is mostly achieved by seeds from adjacent stands, dormant seeds or cones in the forest floor, or

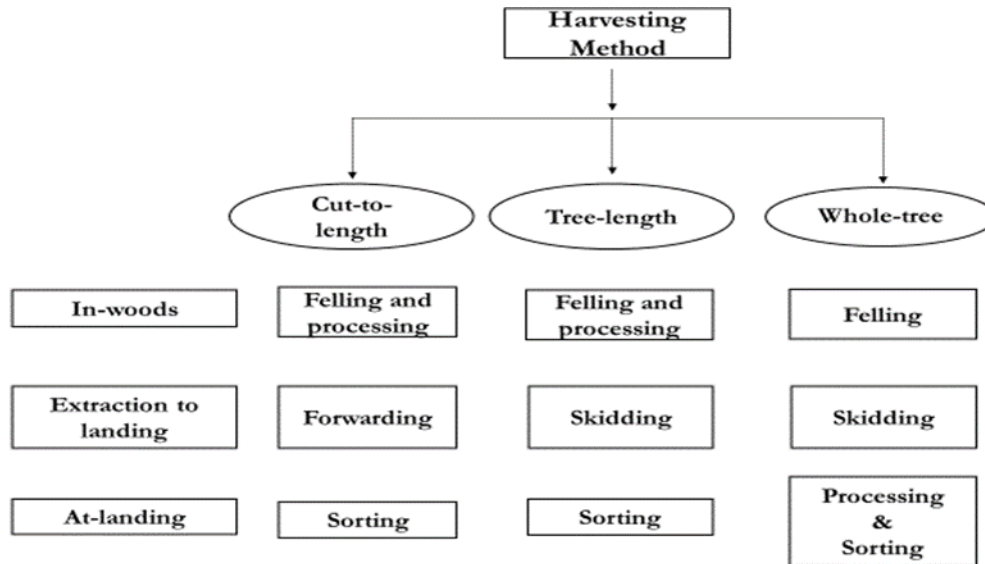
sprouts or suckers from the stumps or roots of trees. Artificial regeneration techniques are mainly comprised of seeding and planting of seedlings. There are various types of CC methods based on the differences in spatial patterns. During 2017, almost 9,196 ha of land was subjected to CC in Maine and accounted for 6.8% of total harvested hectares (MFS 2018).

PH is mostly done to aid advance regeneration under the shade of a mature overstory and to ensure continuous financial returns from the stands. The shelterwood system and its variants such as overstory removal, diameter-limit cut, etc. are the common PH techniques followed in the region. In Maine, around 125,112 ha of land was subjected to PH during 2017 (MFS 2018). During that time, while the total area in CC increased by 8% compared to the previous years, there was a decrease of 2% in PH prescription (MFS 2018). The probability of successfully establishing natural regeneration is much higher in PH when compared to CC. Most of the time, only limited options are available as the CC stand might be covered by competitors (undesired species) or a seed source is not available (Ashton & Kelty 2018).

CC has been found to be more operationally productive than variants of PH such as diameter-limit cut, crop tree release, shelterwood cut and overstory removal (Wilson & Wilson 2001; Li et al. 2006; Soman et al. 2019). This can be justified as CC harvests higher amounts of wood compared to PH. Operational productivity is also found to vary for different PH strategies based on the removal intensity (Hiesl et al. 2017). Percentage of growing stock and mature trees to be left in the stand as decided by the silvicultural prescription also influence the selection of harvesting equipment and methods. Chapter 2 of this study compares CC and PH, and Chapter 3 studied a variant of CC (strip cutting) under different harvesting methods.

## 1.4. Harvesting Method

Harvest method is distinguished based on the form in which timber is extracted to the landing, in other words, the location of processing (i.e., at the stump or landing). Harvesting methods are broadly classified into whole-tree (WT), cut-to-length (CTL), and tree length (TL) (Figure 1.2).



**Figure 1.2.** Comparison of the operational phases in different harvesting methods (Kellogg et al. 1993).

The harvesting system is the practice by which wood is extracted to the landing and can be classified into ground-based, cable yarding and aerial systems. While cable yarding is performed on steep terrains (slope more than 40%), aerial systems (using helicopters) are restricted in use and are the most expensive among the three. Ground-based harvesting is the most common system employed in the northeastern US region and is the least expensive.

WT is the most commonly practiced method in Maine, followed by CTL and TL (Leon & Benjamin 2013). Machinery used in WT harvesting is a feller-buncher, grapple skidder, stroke-boom delimber and slasher/loader. CTL generally employs more advanced machinery like a harvester/processor and a forwarder, which have better fuel efficiency (Ponsse 2005). The TL

method uses a chainsaw and cable skidder. In the TL method, logs are semi-processed before they reach the landing. Final processing or bucking is done by a slasher at the landing to cut the logs as per market requirements. It is somewhat a mixture of WT and CTL methods. In the New England region of the US, a different form of TL method called a hybrid TL (Hyb TL) is often practiced. Chapter 3 of this study discusses a Hyb TL method, where processing is done using a stroke-boom delimber deployed at the stump (inside the unit) and extraction is done using a grapple skidder.

Operational productivity and cost of WT method are markedly different than CTL and TL. Weekly productivity of WT method has been reported to be almost 2.5 times more than that of CTL (Li et al. 2006). Other studies comparing costs of WT and CTL have given contradicting results wherein CTL cost was 15-30% higher, similar or relatively lower than that of WT harvesting (Gingras & Favreau 1996; Lanford & Stokes 1996). This variation in the cost of operations can be attributed to the differences in volume removed, operational and stand conditions. Limited studies have actually looked into the costs and productivity of TL method. Available results show that TL method was slightly less expensive when compared to WT method (Zundel & Lebel 1992).

### **1.5. Climate of the Region**

Geographically, Maine lies in the temperate region experiencing extreme freezing climate with winter temperatures dropping down to -30° C. Anecdotal sources suggests that almost 70% of the harvesting operations in the region occur during the winter season, i.e. from November to end of March. One of the major reasons for favoring winter harvesting is the minimum disturbance caused to the ground compared to that of summer harvesting. Bates et al. (1993)

found that the soil disturbances caused by summer logging were nearly five times more than that caused by winter logging. Some effects of winter harvesting on operational productivity are discussed in Chapter 3.

## **1.6. Forestry Best Management Practices (BMP)**

Site disturbance is an unavoidable aftereffect of mechanized harvesting operations and varies in the degree of severity (Han 2007). Site disturbances are mostly in the form of soil disturbances (including compaction, displacement, and rutting), which may greatly reduce the overall site quality and future yield (Labelle & Jaeger 2011). These disturbances are mostly concentrated along skid trails and landings with maximum degree of disturbance occurring during the initial few machine passes (Han et al. 2006).

BMPs are practices intended for controlling the site disturbances occurring during forest operations (Helms 1998). These BMPs include but are not limited to proper planning, covering skid trails with slash mats, maintaining buffer strips, closing roads or trails after the harvesting operation, operating in a specific seasonal timeframe, using designated skid trails, and minimizing the number of machine passes (Aust & Blinn 2004). Based on the physical location of implementation, BMPs can be broadly classified into: (1) Road BMPs (structural installations such as culverts, ditches, and road crossings intended to minimize the velocity of water flow and/or disperse the quantity of water), and (2) Operational BMPs (strategies adopted mostly during timber harvesting operations within the stand to primarily prevent soil disturbance) (Soman et al. 2019). Appropriately installed BMPs have been found to distinctly benefit soil and water quality (Cristan et al. 2016). BMPs also include post-harvest soil remediation strategies like tilling, seeding, subsoiling, and installing water bars to rectify soil disturbances (Conrad et

al. 2012; Lloyd et al. 2013; Contreras et al. 2016). There have been several studies that have analyzed different BMPs practiced in different parts of North America (Table 1.1). All these BMP measures involve additional costs, resulting in an increase in operational costs (Sawyers et al. 2012).

**Table.1.1.** Findings from studies conducted in different parts of North America on forestry best management practices (BMPs).

Publication	Region	BMP studied	Major findings
Hornbeck et al. (1986)	New Hampshire	Minimizing harvest size	Progressive strip clear-cutting more efficient than total clear-cut for maintaining water quality
Bates et al. (1993)	Minnesota	Seasonal harvest <sup>1</sup>	Soil disturbance nearly five times more in summer harvest when compared to winter harvest
McDonald & Seixas (1997)	Alabama	Slash <sup>2</sup>	Effective in controlling soil disturbances
Vowell (2001)	Florida	Maintenance of buffer strips	Effective in preserving water quality
Han et al. (2006)	Idaho	Seasonal harvest <sup>1</sup> , slash <sup>2</sup> and designated skid trails	Quantified common strategies used in reducing soil disturbances 1. Increase in slash <sup>2</sup> layer 2. Use of designated skid trails 3. Harvesting during dry seasons
Wilkerson et al. (2006)	Maine	Maintenance of buffer strips	Effective in maintaining water quality
Gan & Smith (2007)	Texas	Slash <sup>2</sup>	Increases the water quality and long-term site productivity
Han et al. (2009)	Idaho	Slash <sup>2</sup> and designated skid trails	1. Heavy slash <sup>2</sup> reduces soil compaction by up to 210% 2. Use of designated and historic skid trails –an effective BMP
Clinton (2011)	North Carolina	Maintenance of buffer strips	Protects stream water quality
Labelle & Jaeger, (2011)	New Brunswick (Canada)	Seasonal <sup>1</sup> harvest and slash <sup>2</sup>	1. Seasonal harvest <sup>1</sup> effective in controlling site disturbances 2. Slash <sup>2</sup> controls increase in soil bulk density
Wear et al. (2013)	Virginia	Slash <sup>2</sup> , mulch and mulch + silt fence treatment	Compared different BMP strategies and found skid trails with logging slash <sup>2</sup> was most cost effective
Nolan et al. (2015)	Virginia	Stream crossing, skid trail patterns and slash <sup>2</sup>	1. Skid trail stream crossings have greater potential soil



Table 1.1 Continued

			erosion rates than truck road stream crossings 2. Lower skid trail slopes (<15%) recommended for skidder stream crossing and use of slash <sup>2</sup> for stabilizing bare soil areas suggested
Kelly et al. (2017)	Northeastern U.S	Slash <sup>2</sup> , stream crossing, water bar and broad based dip	Impacts of BMPs affected by – machinery, labor costs, crew size, and overall system productivity
Soman et al. (2019)	Maine	Slash <sup>2</sup> and skid trail pattern	1. Extent & severity of sensitive ground directly related to extraction cost 2. Parallel pattern of skid trail is the most effective

<sup>1</sup>Timber harvesting is centered in particular seasons of the year when the ground is dry or frozen

<sup>2</sup>Armoring machine trails with slash

Utilization of harvest residues as slash mats is a common operational BMP adopted in the northeastern US. Slash mats spread over the skid trails provide a cushioning effect and shield the soil profile and enhance machine productivity on sensitive grounds (Labelle & Jaeger 2018). Despite the wide acceptance and use of BMPs, much less has been done to evaluate the costs of implementation. Chapters 2 and 3 analyze and explain BMP costs and the factors influencing the implementation costs.

In a nutshell, this research was conducted to aid the forest management sector in the New England region with harvesting costs and productivity information for comparing different harvesting scenarios unique to the region. Chapter 2 compares the productivity between different variations of a CC and a PH, and discusses the major factors affecting production economics of the timber harvesting operations. Chapter 3 compares a Hyb TL method with a conventional WT method and discusses the economic and ecological feasibility of employing a stroke-boom delimber in-woods. The cost of implementing BMPs has also been evaluated in both studies and management implications have been suggested.

## **1.7. Organization of the Thesis**

The thesis is comprised of three chapters, out of which two are full-length manuscripts. Chapter 1 serves as an introduction to the thesis. Chapter 2 has been published in the “*International Journal of Forest Engineering*”. Chapter 3 compares different harvesting methods with a focus on at-stump processing. It is organized in the form of a full length manuscript as it is intended to be submitted to “*Forest Ecology and Management*”. Since the organization of the thesis is in the form of two full manuscripts, several statements, ideas, and findings may be restated in different chapters. The final chapter intends to provide an overall summary of the entire thesis by briefly discussing the significance of the study.

Furthermore, the results of Chapter 2 and 3 have been presented at various regional, national, international conferences and field demonstrations such as the Society of American Foresters Convention 2017, Council of Forest Engineering Annual Meeting 2018 and Bi-Annual Eastern Canada – USA Forest Science Conference, 2018.

## **CHAPTER 2:**

### **IMPACTS OF SILVICULTURAL PRESCRIPTIONS AND IMPLEMENTATION OF BEST MANAGEMENT PRACTICES ON TIMBER HARVESTING COSTS**

#### **2.1. Abstract**

Rising costs of forest operations and decreasing revenue generated from harvesting are becoming critical challenges in forest management throughout the Northeastern US. Along with this, the low markets for comminuted forest residues and stricter policies on environmental protection have prompted utilization of these materials as slash mats on skid trails for minimizing soil disturbances. The aim of this study was to evaluate the cost of different silvicultural treatments and utilization of forest residues generated from a mechanized timber harvesting operation for implementing Best Management Practices (BMPs). The field based experiment was done in central Maine, where four forest stands were managed at varying intensities following silvicultural prescriptions common to the region (partial harvest (PH) and clear-cut (CC) treatments). Variables measured included delay free cycle times of various timber harvesting machines, predictor variables, and stand features. The total cost of PH was higher than that of CC (\$22.94 m<sup>-3</sup> versus \$14.88 m<sup>-3</sup>). Of the various operational phases, the costs associated with extraction was the highest and ranged from 52 to 70% of the total cost for PH and CC, respectively. The cost of BMP implementation was estimated to be between \$10 and \$52 PMH<sup>-1</sup> or \$1.0 and \$3.7 m<sup>-3</sup>, and was influenced by several factors, including machine maneuverability and the extent of area which demanded BMP implementation. This information on the cost and productivity for timber harvesting operations, along with BMP implementation, will support the development of economic and environmentally sustainable harvesting strategies.

## **2.2. Introduction**

Timber harvesting is a high capital intensive business, and therefore the economic feasibility of operations is an important consideration in forest resource management. Operation managers can use information about productivity of harvesting equipment in varying stand conditions to improve the efficiency, in both time and economics, of their harvesting operation (Hiesl 2015). The variables that are found to impact productivity and costs of harvesting can be broadly classified into stand and operational variables. Stand variables, which primarily relate to site conditions and prescription, may include presence of water bodies, topography, slope profile, volume and species of wood harvested per hectare, and size of harvesting unit. Operational variables include but are not limited to silvicultural prescriptions, harvesting methods, skidding distances, number of logs per turn (volume per turn or weight per turn), crew size and expertise, equipment specification, maneuverability, and market value for the end-products (Han et al. 2004; Hiesl 2013). Of these operational variables, silvicultural prescription may significantly affect the productivity and costs of harvesting operations (Wilson & Wilson 2001).

### **2.2.1. Silvicultural prescription**

Silvicultural prescription for a stand is mostly related to the institutional functionality desired by the forest (Nyland 2016) and is determined by the objectives of stand management, market requirements, desired post-harvest stand conditions, laws and policies that regulate harvesting (Davis 1966). From a forest resource utilization perspective, silviculture prescription is critical in determining the future yield from the stand. Silviculture prescription determines the type, quality, and quantity of wood to be harvested. Li et al. (2006) reported harvesting production and costs were primarily affected by silvicultural prescriptions and logging machinery utilized.

Harvesting recommendations provided in silvicultural prescriptions specify trees to remove during the operation, which eventually determines the percentage of the stand to be harvested. Both tree size and harvesting intensity directly influence productivity of the harvesting operation. A CC prescription conventionally remove larger volumes of timber than a PH, making it commercially more attractive from an operational perspective. Studies have shown that in ground-based harvesting, the cost for PH techniques (such as a shelterwood system) was almost 109–138% compared to CC costs (Wilson & Wilson 2001). Furthermore, within PH itself, operational cost can vary based on the removal intensity (Hiesl 2015; Hiesl et al. 2017)

#### 2.2.2. Best management practices (BMPs) in forest operations

Efficiency of operation can be considered in financial as well as ecological terms. Eco-efficient mechanization of forest operations focuses on minimizing negative impacts on forest stands as well as on economic profit (Nugent et al. 2003). Soil compaction, displacement, and rutting are can reduce the overall site quality and may result in future yield loss. Detrimental effects of soil disturbances that have been documented include inducing physical root damage, reducing soil porosity thereby limiting infiltration for both water and air (Naghdi et al. 2016), introducing pathogens through the damaged portions of roots (Thor & Stenlid 2005), restricting soil fauna activity and fine root development (Page-Dumroese et al. 2010), and mobilizing heavy metals (Pierzchała et al. 2016). All of these effects eventually lead to reduction in tree growth and stand productivity (Clayton et al. 1987; Kranabetter et al. 2006). Some of these negative effects can remain significant 5 years following the harvest (Labelle & Jaeger 2011). As preventive measures are found to be more economically and environmentally beneficial than remedial practices (Han 2007), several strategies have been developed to reduce the impacts of harvesting on the soil profile. A common operational BMP adopted in the Northeastern US is the utilization

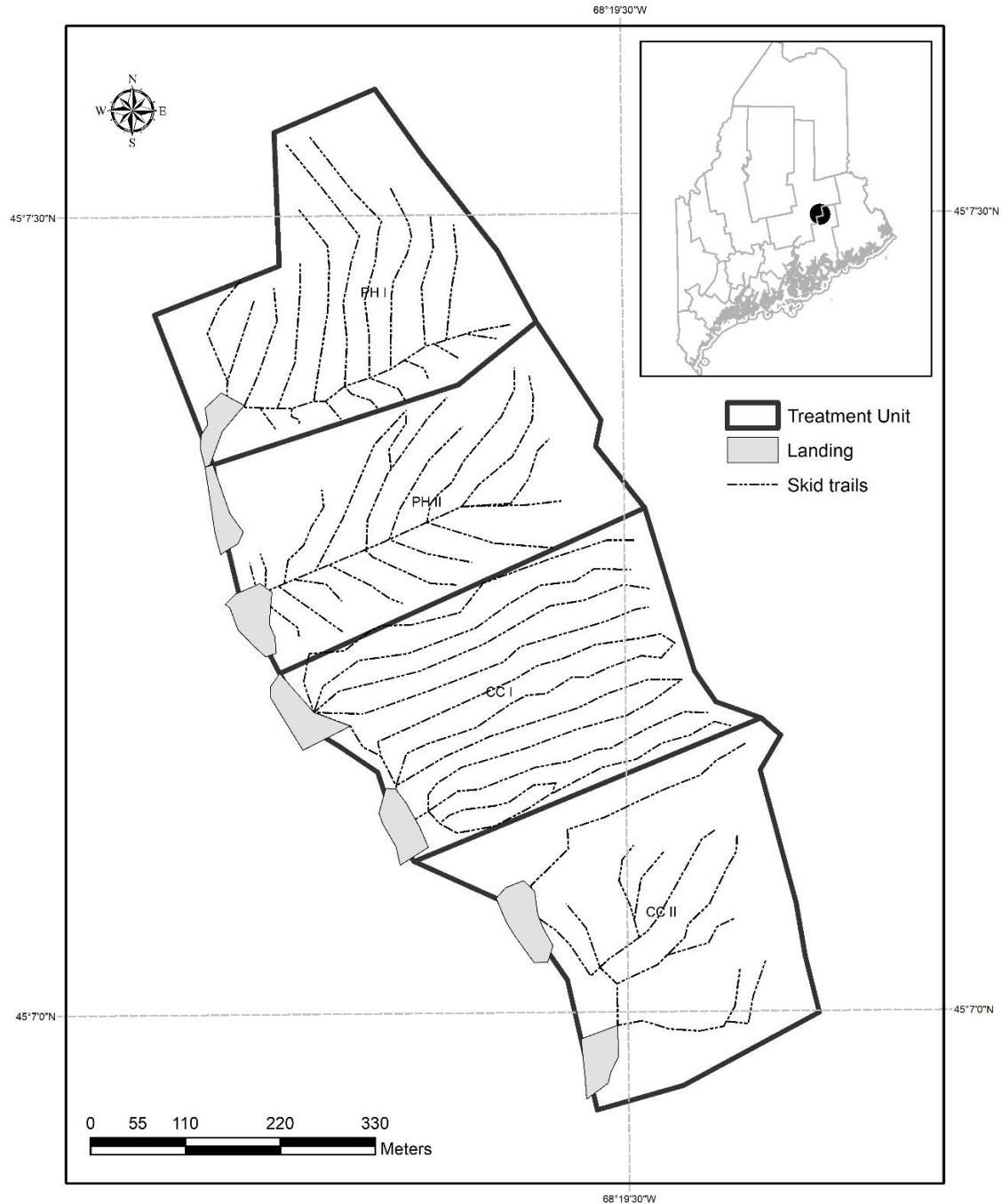
of slash (harvest residues from processing of timber, mostly in the form of tree tops and branches) on skid trails to help cover the susceptible soil horizons. This layer of slash over the trails acts as a corduroy and shields the exposed roots, thereby preventing injuries. Furthermore, use of harvest residues has been found to improve economic feasibility of some silvicultural prescriptions by reducing site-preparation costs (Gan & Smith 2007). Covering trails with slash and ensuring its continuity on the trails has been found to be critical in limiting the severity of soil disturbance (Han et al. 2009). Several studies have highlighted the quality and effectiveness of these and other BMPs (Wilkerson et al. 2006; Edwards & Williard 2010; Clinton 2011); as a result, BMPs to promote sustainability have been mainstreamed into forest management. Despite this wide use, much less has been done to evaluate the costs of implementation. Though overall implementation rates of BMPs are believed to be high, additional research is needed regarding specifics of forestry BMPs to maximize efficiency and potentially reduce costs (Anderson & Lockaby 2011). The goal of this study was to evaluate and compare the operational efficiency and cost of timber harvesting systems employed in different silvicultural prescriptions. The specific objectives were to determine: (1) hourly production rate for each operational phase, and the operation as a whole for contrasting silvicultural prescriptions, (2) the costs associated with implementing BMPs, and (3) the major factors affecting the overall cost and productivity of the timber harvesting operation.

## **2.3. Materials and methods**

### **2.3.1. Study area**

The study was conducted in Grand Falls township in Penobscot County, central Maine (45°7' 17.399" N, 68°19' 47.349" W; Figure 2.1). The study site consisted of a mixedwood forest

(hardwood and softwood) dominated by eastern hemlock (*Tsuga canadensis* (L.) Carr.) and yellow birch (*Betula alleghaniensis* Britt.). Other predominant species include balsam fir (*Abies balsamea* (L.) Mill.), aspen (*Populus spp.*), American beech (*Fagus grandifolia* Ehrh.), red spruce (*Picea rubens* Sarg.), white birch (*Betula papyrifera* Marshall), and white pine (*Pinus strobus* L.). The previous harvest was most likely done using chainsaws and cable skidders in the early 1980s. The climate of the region is characterized as cold and temperate with winter temperatures as low as  $-30^{\circ}\text{C}$ . Average temperature of the region is  $7^{\circ}\text{C}$ . The rainfall here averages 115 cm. The average maximum temperature and maximum precipitation during the harvesting time was around  $23^{\circ}\text{C}$  and 4 cm, respectively. Average elevation of the site was about 30 m above mean sea level. Soil types were predominantly Howland silt loam and Monarda-Burnham complex. These soils, glacial in origin, were poorly drained, gravelly silt loams with a depth to hardpan of 30–50 cm. The slope of the site was uniform and relatively flat ( $<9\%$ ).



**Figure 2.1.** Map showing the treatment blocks, landings, and skid trails for the study area. Partial harvest I (PH I) and partial harvest II (PH II) had a herring bone pattern for skid trails. Clearcut I (CC I) and clearcut II (CC II) were hockey stick- and dendritic-patterned skid trails, respectively.



### 2.3.2. Silvicultural prescription and treatments

The site was subjected to PH and CC silvicultural prescriptions (Table 2.1). For each of the two prescriptions, two contrasting treatments were implemented to capture extremes in market conditions and landowner objectives. PH is defined as the establishment of even-aged reproduction under the shelter of seed trees by removing mature trees in a series of cutting (Nyland 2016). CC is the removal of trees from the entire stand in one cutting with reproduction obtained artificially or by natural seeding from adjacent stands. While CC represents extreme harvest intensity, PH signifies intermediate intensity.

#### 2.3.2.1. Partial harvest (PH)

Two different PH treatments were carried out with the general objective of reducing existing basal area (BA) by half or up to  $15 \text{ m}^2 \text{ ha}^{-1}$ . The difference was in the pecking order between PH I and PH II resulted in a diameter-limit cut and crop tree release, respectively. In the diameter-limit cut (PH I), all trees from which a sawlog could be obtained (DBH of 15 cm and above) were harvested, whereas in the crop tree release (PH II), most of the sawlog trees were retained with the intention of enhancing growing conditions for the residual stand.

**Table 2.1.** Silvicultural prescriptions, area, number of plots, and trees inventoried for each individual treatment implemented in each partial harvest (PH) and clear-cut (CC) treatments.

Treatments	Silvicultural prescriptions	Area (ha)	Number of plots	Trees inventoried
<b>PH I</b>	Diameter-limit cut	10.12	7	33
<b>PH II</b>	Crop tree release	10.52	9	72
<b>CC I</b>	Overstory removal	11.33	8	78
<b>CC II</b>	Clean clear-cut	10.93	10	65

#### 2.3.2.2. Clear-cut (CC)

The prescription for both CC I and CC II were similar, except for the minimum DBH of trees removed. For CC I, the minimum DBH of trees removed was 13 cm, whereas for CC II the minimum DBH was 5 cm. Therefore, CC I was considered an overstory removal and CC II was a “clean” clear-cut. In all prescriptions, smooth-barked beech, oak, snags, boundary, and cavity trees were retained for wildlife purposes. Large, non-veneer quality yellow birch trees were also retained approximately 60 m apart as seed trees and for wildlife purposes.

#### 2.3.3. Stand inventory

At 10% sampling intensity, 34 plots were inventoried prior to and post-harvest using 20 Basal Area Factor (BAF) variable radius plots for all trees measuring above 8 cm DBH. Parameters recorded included species, DBH, and geographical coordinates for the plot center. Tree heights were measured for every sixth tree of a given species. Dead snags and diseased trees were recorded separately. The inventoried trees were also examined for any deformities such as rot, twists, broken tops, and holes. Basal area per hectare ( $\text{m}^2 \text{ha}^{-1}$ ) and stand density ( $\text{trees ha}^{-1}$ ) were calculated for each prescription.

#### 2.3.4. Harvesting operation

A ground-based, whole-tree harvesting operation was carried out on an industrial level during July and August of 2017. All four treatments were laid on a single stretch of forest land. The machines used, and the operators remained the same for all treatments. There were eight researchers involved in field data collection, whose experience ranged from 0–8 years of working on timber harvesting operational research (0 being conducting time and motion study for the first time). All researchers were trained for an entire day prior to the actual data collection. The

harvesting process was divided into the following operational phases: felling, extraction, processing, sorting and loading.

#### 2.3.4.1. Felling

The harvesting operation initiated with a feller-buncher (John Deere 753G). There were three components within this operational phase, which were timed: travel empty, cutting, and bunching. Each delay free cycle (DFC) started as the machine traveled empty to a tree (travel empty), followed by cutting trees (cutting). The machine then rotated holding the felled trees and placed them into a new or existing bunch (bunching), marking the end of the cycle (Table 2.2). The distance moved by the machine for each cycle element was visually estimated; distance markers were set on the harvest unit at frequent intervals prior to the operations to aid in this estimation. The felling and subsequent extraction operational phases were decoupled, with the feller-buncher operating one week prior to the skidder.

#### 2.3.4.2. Extraction

Extraction was done using two grapple skidders (CAT 625 G), which brought all trees to the landing for processing. The skid trails were tracked using GPS units mounted on the skidders. The DFC for the skidder started when the machine traveled empty from the landing to the unit (travel empty). As the machine reached the bunch, it re-positioned itself for grappling the trees (positioning). Grappling initiated when the skidder started grappling the bunch; if a grapple was dropped and picked up again, it was considered as re-grappling. Followed by which, the machine carried the pile to the landing (travel loaded). The travel loaded ended when the skidder reached the landing and dropped the bunch (dropping grapple). In addition to these components, two other cycle components were also recorded: picking up slash (at landing), and handling slash (in unit) (Equation 2.1, Table 2.2). Pieces (stems) having a large-end diameter  $\leq 11$  cm were

regarded as slash. The distance covered for each cycle component as well as the diameter and number of logs carried during each cycle were recorded, determined by ocular assessment.

Equation 2.1: Cycle components involved in the delay free cycle (DFC) time calculation for extraction and BMP implementation

$$DFC = \text{Travel empty} + \text{Picking up slash}^* + \text{Positioning} + \text{Grappling} + \text{Re-grappling} + \text{Travel loaded} + \text{Dropping grapple} + \text{Handling slash}^*$$

\*Cycle components only present for the BMP skidding cycle and not a part of the non-BMP cycles.

**Table 2.2.** Cycle elements and predictor variables recorded for each operational phase. An operational phase is defined as an activity that alters the form or location of wood.

Operational phase	Cycle elements	Recorded predictor variable(s)
Felling	Travel empty	Trees cut per cycle
	Cutting	Tree species
	Bunching	Butt-end diameters (cm)
		Distance between trees (m)
		Distance to bunch (m)
Extraction	Travel empty	Distance to the bunch (m)
	Travel loaded	Loaded distance (m)
	Dropping	Number of pieces
	Picking slash	Diameters for each piece (cm)
	Cleaning landing	Distance traveled for picking slash (m)
	Positioning	
	Grappling	
	Re-grappling	
	Handling slash	
Processing	Grappling	Tree species
	Processing sawlog	Butt-end diameters (cm)
	Decking sawlogs	Number of cuts
	Piling biomass	Number of 3 m, 6 m, and 9 m logs
Loading and sorting	Swing empty	Diameter of logs (cm)
	Grapple	Number of logs handled per turn
	Cutting	
	Swing loaded	
	Sorting	

#### 2.3.4.3. BMP cycles

As a part of BMP implementation, residues of timber processing (slash) such as limbs, offshoots, and broken logs, were carried back to the unit from the landing by the skidder and dropped on susceptible pockets of the trail with the intention of protecting the soil profile. Thereby, skidder DFC time was broadly classified into BMP and non-BMP, based on whether slash was handled during the respective cycle. The primary time component within the BMP DFC initiated when the skidder picked up slash at the landing (picking up slash time) (Equation 2.1). Handling slash time was the time required for the skidder to position itself on a particularly susceptible point on the trail and scatter slash over the trail. Frequently, the skidder would then run over the dropped slash material with the intention of setting it (which also formed a part of handling slash time). Travel empty time was not considered as a part of the BMP DFC, as the skidder would need to reach the bunch anyway for performing its regular function. Time required for implementation of BMPs in the treatments was calculated by adding the average values of time taken for the aforementioned time components (Equation 2.1).

#### 2.3.4.4. Processing

A stroke-boom delimber (John Deere 200 LC) was used for processing the trees at the landing. DFC for delimber began when the grapple swung empty to the pile brought by the skidder (swing empty). This was followed by grappling the log (grapple), swinging loaded, processing the log, and ending the cycle when the log was placed in a deck (decking). Length of a processed log was classified by visual estimates into three categories: 3 m (10 ft or below), 3–6 m (10–20 ft), and 9 m (20 ft) or above (Table 2.2). The delimber began its operation two days after the extraction was initiated which helped in decoupling processing from extraction.

#### 2.3.4.5. Sorting and loading

The sorting of sawlogs began with the processor and was finalized by the slasher. Sorting and loading were only done for merchantable wood by using a slasher. Merchantable wood in this study constituted sawlogs and pulpwood. Both loading and sorting had similar cycle components, which started when the machine swung empty to the deck of logs (swinging empty). This was followed by grappling the log, swinging loaded, and ended when the log was placed in separate log piles (sorting), or on the log truck (loading) (Table 2.2).

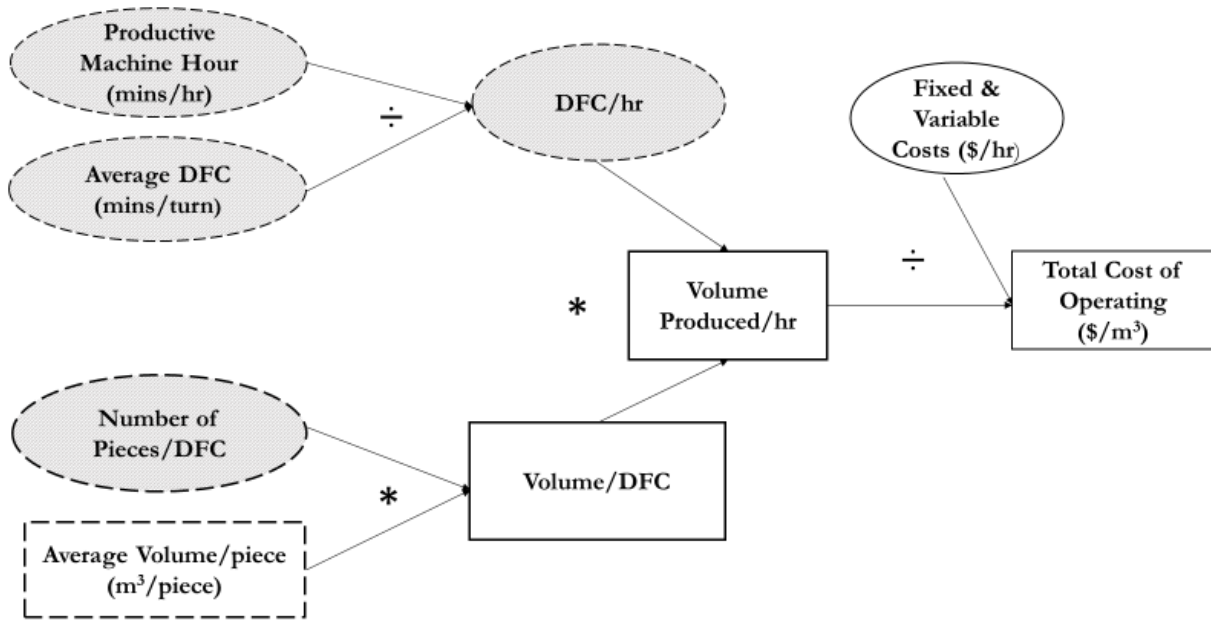
#### 2.3.5. Machine rate calculations

DFC time for all operational phases for all the treatments were observed and the average was calculated separately for each treatment. The contribution of each component to the average DFC time was expressed as a percentage. Along with the time components, predictor variables expected to affect cycle time were recorded (Table 2.2). Machine rates were calculated using the standard method by Miyata (1980). Delays were recorded to better understand the factors that influenced productivity and were further classified into mechanical, operational, and personal delay (Kizha & Han 2016). The operational cost for the individual silvicultural treatments were evaluated as a cumulative productive machine cost incurred during the performance of the various operational phases. Purchase prices, salvage values, economic life, utilization rate, wages, and benefits for the crew were obtained from the logging company that owned and operated the equipment (Table 2.3). The fuel price was set at \$0.60 L<sup>-1</sup> and reflected the market price at the time of the operation.

**Table 2.3.** Machine rates and other costs of the equipment used in the harvesting, not including support vehicles such as fuel trucks and personal vehicles. The fuel cost was estimated to be \$0.60 L<sup>-1</sup>. Machine rate per productive machine hours (\$ PMH<sup>-1</sup>) were calculated using the values of 2200 scheduled machine hours (SMH)/year, 10% interest, and 3% insurance (as provided by the company that operated and owned the machines).

Factor	Felling	Extraction	Processing	Sorting and Loading
Make and Model	John Deere 753G, (2008)	CAT 625 G, (2011)	John Deere 200 LC, (2004)	Serco 300, (2008)
Purchase price (\$)	275,000	320,000	345,000	200,000
Salvage Value (\$)	52,250	73,600	34,500	50,000
Variable and operating cost (\$ PMH <sup>-1</sup> )	37.36	53.10	76.85	28.03
Labor cost (\$ PMH <sup>-1</sup> )	42.86	43.08	35.00	39.75
Fuel use (L PMH <sup>-1</sup> )	18.93	22.71	22.71	22.71
Utilization (%)	70	65	80	80
Machine rate (\$ PMH <sup>-1</sup> )	127.38	153.86	171.36	99.66

Hourly machine costs in dollars per productive machine hour (\$ PMH<sup>-1</sup>) were calculated using standard machine rate calculation methods (Figure 2.2). Scale tickets for the wood products were obtained from the forest management company. The average sawlog piece size (in cubic meters) was determined for each treatment by randomly scaling 991 sawlogs from different log decks.



**Figure 2.2.** Flow chart for machine rate calculation. The signs indicate the mathematical calculations involved transitioning from one value to the next. Dashed grey ovals indicate data obtained from the detailed time study, dashed rectangles include information obtained from scaling log decks and scale ticket information, and solid ovals indicate information from machine rate calculations. All other shapes include values obtained through calculations.

### 2.3.6. Statistical analysis

The datasets were initially screened for outliers using 95% confidence intervals, after which scatterplots were developed for each variable to determine whether the relationships between transformed independent and dependent variables were linear. The sorted data were used for developing regression models in IBM SPSS Statistical Software. For the regression analysis, DFC and its variants (Log DFC and Ln DFC) were treated as the dependent variable and the independent ones were the variables collected that did not involve any time component. Dummy variables were used to represent species and researchers. Several transformation models were developed and compared; models that met the assumption of normality and had higher adjusted  $R^2$  values were selected. Multi-collinearity was tested using a tolerance value greater than 0.1 and variance inflation factor (VIF) less than 10. Machine rate calculations were done by



standardizing the variables for the silvicultural treatments. Standardized variable comparison helped elucidate differences in productivity due to the treatment, irrespective of variation in stand conditions (Kizha & Han 2016). To estimate the actual volume harvested from each silvicultural prescription, a ratio was developed using volume obtained from scaling the log decks and scale ticket provided by the forest management company. This was done primarily to capture the variation in the population due to sampling. Scaling was done during the operation measuring small-end and large-end diameters (cm), along with the length (m) of the logs from different sorts. Analysis of variance (ANOVA) was conducted to determine if there were any differences in DBH of trees among the different treatments.

## **2.4. Results**

### **2.4.1. Inventory analysis**

A total of 248 trees were measured from 34 plots, of which 7, 9, 8, and 10 plots belonged to PH I, PH II, CC I, and CC II treatments, respectively, prior to harvest. Tree count from the plots in PH I, PH II, CC I, and CC II were 33, 72, 78, and 65 respectively (Table 2.1). In total, 105 trees were inventoried on PH treatment plots and 143 on CC treatment plots. There were no significant differences in the diameter class for trees within the treatment units prior to harvest (ANOVA,  $p = 0.15$ ). The total amount of wood harvested from PH I, PH II, CC I, CC II treatments were 1151, 1031, 1913, and 1887 metric tons, respectively (obtained from scale tickets). Pre- and post-harvest stand density and basal area  $\text{ha}^{-1}$  were calculated for all four treatments (Table 2.4).

**Table 2.4.** Stand density (trees ha<sup>-1</sup>) and basal area (m<sup>2</sup> ha<sup>-1</sup>) attributes based on 10% pre- and post-harvest stand inventory using 20 Basal Area Factor variable radius plots for the partial harvest (PH) and clear-cut (CC) treatments.

Treatment	Pre-harvest		Post-Harvest	
	Stand density	Basal area	Stand density	Basal area
PH	4049	358	2947	231
CC	1263	393	779	124

#### 2.4.2. Harvesting operation

Regression analysis and standardized comparison were initially performed on all four treatments separately. The adjusted  $R^2$  values ranged from 0.32 to 0.57 for felling and 0.15 to 0.32 for processing (Table 2.5).

**Table 2.5.** Regression models developed for predicting delay free cycle time (DFC) in minutes using standardized comparison. All units are in cm for DBH and m for distance. Dummy variables were used for researcher and species.

Machine	Prescription	Adjusted $R^2$	Standardized models predicting DFC
<b>Feller-Buncher</b>	PH	0.42	DFC = 0.99 + 1.05 (Distance between trees) + 0.83 (Average diameter/cycle) + 1.02 (Distance to bunch) + 4.02 (Number of trees cut/cycle)
	CC	0.45	DFC = 19.45 + 0.35 (Distance between trees) + 0.43 (Average diameter/cycle) + 0.32 (Distance to bunch) + 3.98 (Number of trees cut/cycle) – 2.050 (Researcher)
<b>Delimber</b>	PH	0.25	Ln DFC = 2.40 + 0.06 (Average diameter/cycle) + 0.20 (Number of cuts) – 0.14 (Number of 3 m logs) – 0.10 (Number of 20 m logs) + 0.34 (Number of logs)
	CC	0.17	Log DFC = 1.32 + 0.02 (Average diameter/cycle) + 0.08 (Number of cuts) – 0.07 (Number of 3 m logs)
<b>Skidder</b>	PH	0.44	DFC = 260.98 + 0.19 (Travel loaded distance) + 7.43 (Travel loaded pieces dia.) + 0.73 (Handling slash distance)
	CC	0.27	Log DFC = 2.33 + 0.001 (Positioning distance)
<b>Slasher</b>	PH		Not significant
<b>(Sorting)</b>	CC	0.50	DFC = 26.20 + 4.70 (Number of logs)

\*PH is partial harvest, CC is clear-cut, Ln DFC is the natural log of DFC, Log DFC is the log to the base 10 of DFC.

For extraction, the model was not found to be significant for PH I and the adjusted  $R^2$  values for other treatments ranged from 0.32 to 0.67. In sorting, the regression model was found to be insignificant for the PH I and PH II treatments ( $p > 0.05$ ). The cost of operation was calculated to be \$49.04, \$32.45, \$36.50, and \$17.14  $\text{m}^{-3}$  for PH I, PH II, CC I, and CC II, respectively (Table 2.6).

**Table 2.6.** Cost (US\$  $\text{m}^{-3}$ ) and productivity ( $\text{m}^3 \text{PMH}^{-1}$ ) of the different phases of the operation for wood handled in the partial harvest (PH) and clear-cutting (CC) treatments.

Operational phase	Cost					Productivity		
	PH I	PH II	Combined PH	CC I	CC II	Combined CC	Combined PH	Combined CC
Felling	1.76	2.65	1.74	1.53	0.74	1.38	101.88	128.72
Extraction <sup>a</sup>	39.76	25.38	15.98	29.58	10.24	7.72	19.07	39.55
Processing	5.96	2.97	3.63	3.69	4.46	3.71	67.41	39.63
Sorting	0.60	0.49	0.63	0.74	0.74	1.11	258.71	146.33
Loading <sup>b</sup>	0.96	0.96	0.96	0.96	0.96	0.96	168.93	168.93
Total	49.04	32.45	22.94	36.50	17.14	14.88		

<sup>a</sup>Cost of extraction includes values for both the skidders used.

<sup>b</sup>Loading cost was same for both treatments as the piles were combined during sorting to facilitate loading of similar market products.

The costs calculated for similar treatments did not show any trends and there was wide variation in costs of similar treatments, such as CC I and CC II. This was primarily due to contrasting stand conditions, such as average skid distance, extent of sensitive areas that required BMP implementation, and volumes removed from each treatment, which resulted in most of the

standardized models having very low  $R^2$  values (Table 2.7). However, when the treatments were modelled broadly based on PH and CC (designated as Combined PH (Comb PH) and Combined CC (Comb CC)), a clear trend was evident (Table 2.5). Additionally, these models had higher adjusted  $R^2$  values compared to the individual treatments. The total cost of operations from stump to truck was estimated to be \$22.94 and \$14.88  $\text{m}^{-3}$  for the Comb PH and Comb CC treatments, respectively (Table 2.6).

**Table 2.7.** Stand attributes based on 10% pre- and post-harvest stand inventory using 20 Basal Area Factor (BAF) variable radius plots for each of the two partial harvest (PH) and clear-cut (CC) treatments.

Stand attributes	PH I	PH II	CC I	CC II
Stand density (trees $\text{ha}^{-1}$ )				
Pre-harvest	687	1,108	2,710	531
Post-harvest	482	187	210	0
Basal area ( $\text{m}^2 \text{ha}^{-1}$ )				
Pre-harvest	22	37	45	30
Post-harvest	19	18	8	0
Skid trails (m)				
Total distance	2,608	2,458	1,668	4,342
Average distance	318	254	408	306
Scale ticket volume (metric tons)				
	1,151	1,031	1,913	1,887

#### 2.4.2.1. Felling

The total number of observations considered for the analysis were 946(outlier-free) from the four treatments. Bunching time represented the largest contribution to the DFC for all the treatments (28–53%), except for the CC II unit in, which travel time was the largest contribution (60%). Most of the predictor variables, such as distance between trees, distance to bunch, average diameter of trees, and number of trees cut per cycle, significantly contributed to the DFCs ( $p < 0.05$ , Table 2.5). For Comb CC treatment, the researcher collecting the data was found to be significant in the model ( $p < 0.05$ ). The felling cost was estimated at \$1.74 and \$1.38 m<sup>-3</sup> for the Comb PH and Comb CC treatments, respectively (Table 2.6).

#### 2.4.2.2. Extraction

The average skidding distance was 360 and 281 m for the Comb PH and Comb CC, respectively. Two skidders were operating simultaneously, hence the final operating cost calculated was for both. A total of 555 skidding cycles were recorded for the two skidders. Travel loaded distance, diameter of the pieces, and distance travelled for handling slash were significant factors in controlling the DFC for the Comb PH treatment. The model of DFC for the Comb CC treatment only had positioning distance as a significant factor ( $p = 0.02$ ). Extraction cost accounted for the maximum contribution in the total cost of operations in the Comb PH as well as Comb CC treatments (\$15.98 and \$7.72 m<sup>-3</sup>, respectively). However, for the Comb CC treatment, the cost of extraction was less than half of the value for the Comb PH treatment.

#### 2.4.2.3. Processing

For the delimber, a total of 1070 DFC observations (outlier-free) were taken from the four treatments. The processing DFC averaged 47.92, 44.03, 50.15 and 42.95 sec for the PH I, PH II, CC I, and CC II treatments, respectively. The log processing task constituted most of the average

DFC, ranging from 64–73%. Regression models showed that for the Comb PH treatment, the average diameter of trees cycle<sup>-1</sup>, number of cuts made, number of 3 m (10 ft or below) logs, number of 3-6 m (10-20 ft) logs and total number of logs processed were significantly related to the DFC (Table 2.5). Processing costs were estimated at, \$3.63 and \$3.71 m<sup>-3</sup> for Comb PH and Comb CC, respectively (Table 2.6).

#### 2.4.2.4. Sorting

Regression models developed for the Comb PH treatment had very low adjusted  $R^2$  values, hence implying that the predictor variables collected were not strongly associated with DFC. For the Comb CC model, DFC was found to be significantly influenced by the number of logs handled. Out of all the operational phases, sorting had the highest adjusted  $R^2$  (0.50) in the Comb CC treatment (Table 2.5). The sorting phase had the lowest cost among all cycle phases for Comb PH. The costs of sorting were determined at \$0.63 and \$1.11 m<sup>-3</sup> for the Comb PH and Comb CC treatments, respectively.

#### 2.4.2.5. Loading

The logs were piled together at the landing, resulting in no difference in cost for this phase between the two treatments. Hence, standardized comparison was not performed for estimating DFC for the loading phase. An average DFC of 35.38 sec was utilized for the machine rate calculation. The average time to load a truck was 29 mins. The cost of loading logs was estimated at \$0.96 m<sup>-3</sup> for all treatments.

#### 2.4.2.6. BMP implementation

Of the 555 skidder DFC, 500 cycles were classified as BMP for all treatments. The BMP cost was calculated using two methods – as a percentage of the skidders' productive machine hour (\$153.87 PMH<sup>-1</sup>) devoted to BMP implementation and the cost per cubic meter of wood

generated (Sahoo et al. 2018). The average time dedicated for picking slash at the landing and handling slash ranged from 1.1–3.8 min and accounted for 7–32% of skidder’s DFC (Table 2.8). The cost of implementing BMPs per cubic meter of wood produced ranged from \$1.00–\$3.70, with the highest costs being reported for the PH II and lowest for CC II (Table 2.8).

**Table 2.8.** The average time taken to implement Best Management Practices (BMPs) in different silvicultural treatments.

<sup>a</sup> Treatment	BMP time <sup>b</sup> (mins.)	Average DFC (mins. turn <sup>-1</sup> )	BMP as % of average DFC	BMP implementation cost	
				(\$ PMH <sup>-1</sup> ) <sup>c</sup>	(\$ m <sup>-3</sup> ) <sup>d</sup>
PH I	3.8	11.8	32	49.8	3.7
PH II	2.4	7.2	34	51.6	2.0
CC I	1.2	5.1	23	35.7	1.2
CC II	1.1	16.4	7	10.0	1.0

<sup>a</sup>PH is partial harvest and CC is clear-cut

<sup>b</sup>Time (in minutes) for implementing BMP was determined by summing picking up slash time, and handling slash from the skidders’ Delay Free Cycle (DFC) time.

<sup>c</sup>Implementation cost calculated as a percentage of the skidders’ productive machine hour (PMH) devoted for BMP implementation. The operational cost per PMH was calculated to be \$153.87.

<sup>d</sup>BMP Implementation cost calculated in \$ m<sup>-3</sup> based on machine rate calculation.

## 2.5. Discussion

Adjusted  $R^2$  values for the DFCs modelled were between 0.17 and 0.50, which showed similar trends to other studies (Hiesl 2013; Kizha & Han 2016). The wide variation in the adjusted  $R^2$  values in each of the treatments can be explained by the difference in number of observations taken, predictor variables selected, along with the many researchers who monitored this operation. Several other predictor variables that might have influenced productivity were not considered in our models. For example, treatment blocks had different site index values, extent of water submerged areas, skidding distances, and trail patterns. Therefore, the cost of operations



might not be solely attributed to the silvicultural treatments. Other studies have reported that factors such as site conditions, species composition, stand density and silvicultural prescription can influence the productivity of the harvesting operation (Andersson & Evans 1996; Nakagawa et al. 2007; Spinelli & Magagnotti 2010). In contrast to these findings, Li et al. (2006) studied five different harvesting methods during a simulation study namely, CC, shelterwood cut, crop tree release cut, diameter limit cut, and selective cut, reported that there was no significant difference in operational cost among the prescriptions. To determine the variation in productivity of the operations due to silvicultural treatment, standardized comparison was performed in this study, and some of the stand factors such as the terrain features were set as constants. The regression model showed that the average diameter of the trees handled per cycle was a critical factor in determining the productivity for the feller buncher and delimber which was in concurrence to the results obtained from previous studies (Kizha & Han 2016). As the silvicultural prescription influences the pecking order of harvested trees, as well as the ease of operation, it substantiates the change in operational productivity over the different treatments. As the same operators and machines were utilized for all the treatments, the influence of factors suggested by Bolding et al. (2009) such as machine productivity and fuel consumption by machines were not of much concern when determining the operational costs.

#### 2.5.1. Felling

As the number of small trees harvested increased, bunching time increased. The contribution of the distance between trees and distance to bunch to the DFC time suggests that high stand density or larger TPH can alter the operational efficiency of felling. Hiesl (2013) reported stand density as one of the most important factors influencing the productivity of felling. Felling productivity was also found to be directly proportional to the tree size (DBH), along with the number of trees

cut per cycle, and inversely to the distance between harvested trees (Kluender et al. 1998; Li et al. 2006; Kizha & Han 2016). The total felling time for all treatments was most affected by the travel distance between trees; this has also been reported by other studies (Wang et al. 2004). Higher cost of felling in the Comb PH treatments compared to the Comb CC can be attributed to the nature of selective felling. Additionally, in Comb PH, the feller-buncher had to move farther without harvesting to reach the next tree to be harvested.

#### 2.5.2. Extraction

Extraction being the costliest component (Table 2.6) and accounted for 70 and 52% of the total cost of operations in Comb PH and Comb CC treatments, respectively. Extraction costs obtained in this study was similar to that reported by Li et al. (2006) (56% of total cost). For the most part, the cost of extraction was directly related to the average skidding distance (Wang et al. 2004; Han et al. 2004; Hiesl 2013). The regression model indicated that implementation of BMPs (slash handling) during extraction did not significantly influence the operational productivity (Table 2.5). More BMP DFCs were recorded in the PH ( $n = 288$  cycles) compared to the CC treatment ( $n = 212$ ), which might have resulted in the cost of PH being much higher than CC.

#### 2.5.3. Processing

In this operation, the processor was considered the bottleneck due to landing space restrictions; skidders had to wait at the landing for trails to be cleared, resulting in operational delays. The landings were continuous roadside in design, and, on average, there were two landings for each treatment. The average diameter of trees per cycle played a significant role in the processing time for the delimber (Hiesl 2013). Li et al. (2006) also reported that the processor was more sensitive to the tree size than the feller-buncher. Based on the results of standardized comparison,

average duration of processing for the Comb CC treatment (Average DFC = 58.80 sec cycle<sup>-1</sup>) was much higher compared to the Comb PH treatment (Average DFC = 33.60 sec cycle<sup>-1</sup>). The actual average DFC time from field data collection, however, showed dissimilar values (46.72 sec and 46.12 sec for Comb CC and Comb PH, respectively). The resulting machine rate calculation values were almost double for Comb CC. This discrepancy was due to the low  $R^2$  for the Comb CC treatment ( $R^2 = 0.17$ , Table 2.5). Therefore, the average DFC time from the field data was considered for evaluating the cost of processing. The slightly increased cost of Comb CC treatment was due to the greater number of small diameter trees processed. Processing cost contributed to about 40% of the total cost in the case of the Comb CC treatments. (Kizha & Han 2016) reported processing cost to increase while dealing with small diameter trees compared to sawlog trees.

#### 2.5.4. Sorting and loading

The regression models developed were found to be significant only for the DFC in the Comb CC treatments ( $p < 0.05$ ). The longer time dedicated to sorting in the Comb CC treatments can be justified as more sorts (based on merchantability) were handled in the treatment (Table 2.7). Loading was not differentiated based on the silvicultural prescription; it was performed to ensure full truck loads for each sorted product. Previous studies have found no significant difference in loading due to the experimental treatments (Kizha & Han 2016). Hence, the total operational cost was calculated by adding the value for loading one cubic meter of wood to the operational costs for both the prescriptions so that a proper comparison could be made between the two silvicultural treatments.

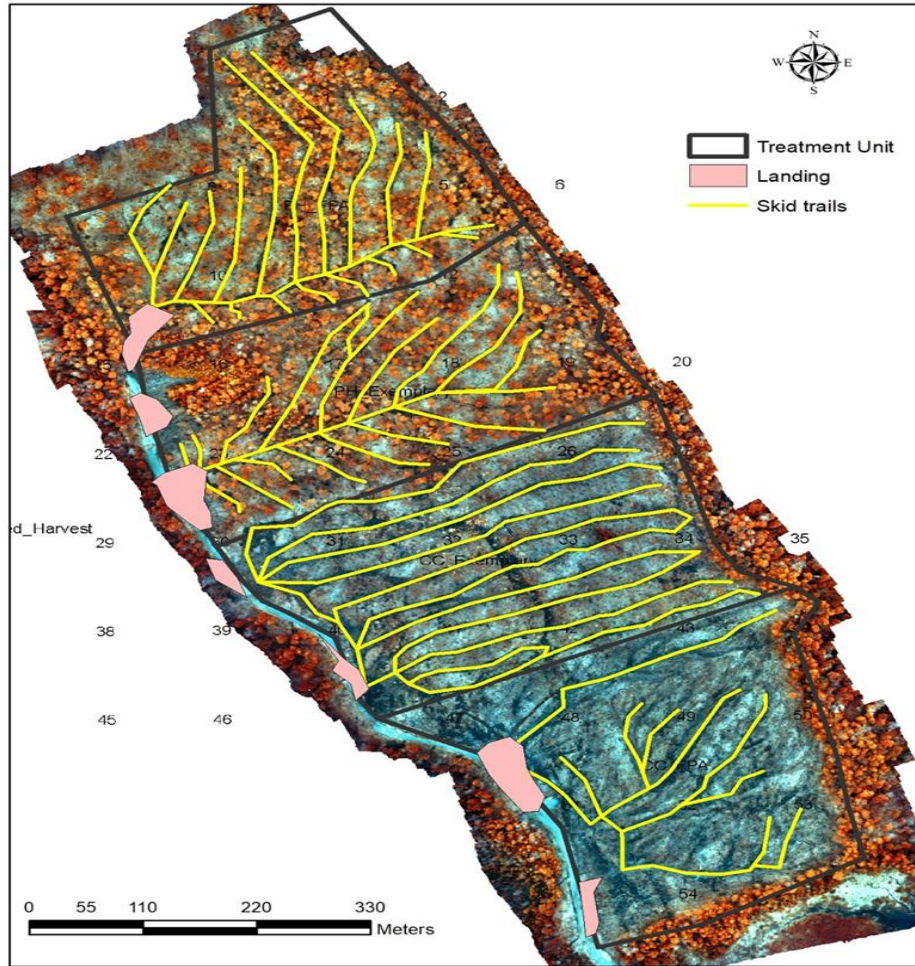
#### 2.5.5. Implications for management

From a managerial perspective, CC operations were easier to execute than PH; PH involved additional pre-harvest planning such as ensuring proper implementation of skid trails, efficient marking of trees to be harvested, and steps that were not necessary for planning the CC operation. During the harvest operations, additional attention was required in PH for both felling and extraction to minimize residual stand damage. Also, in PH, selective felling predictably led to a low intensity of harvesting, thereby limiting the volume of wood harvested. There was a significant difference in the cost of operation per cubic meter of wood handled between the treatments under the different silvicultural prescriptions. In the CC treatments a large number of small-diameter trees ( $DBH < 5$  cm) were handled, which typically lowers productivity and thereby increases the cost of harvesting compared to sawlogs (Han et al. 2004); this contrasts with the results obtained in this study (Table 2.6). This discrepancy can be explained by analyzing the scale tickets, which showed that higher volumes of wood were recovered from the CC treatments than PH, compensating for the expected reduction in productivity due to diameter. The intensity of harvesting was important in determining the total harvesting cost: higher intensities generated high levels of profitability across all product and diameter classes due to the greater volume produced. This contributed to the cost of operations being lower for the CC treatments compared to the PH. These are similar to the results obtained by Kluender et al. (1998), who found that small-diameter classes tend to give higher returns than the large stems when harvest intensity is increased.

#### 2.5.6. Best management practices

The skid trails were designed in “herring bone” and “hockey stick” patterns for PH I and CC I, respectively (Figure 2.1). This was primarily done to minimize skidding over sensitive zones. Sensitive zones are defined as areas that are submerged in water, where the moisture content of the soil is saturated, or that have a stream running through them, and demand BMP installation for using as a skid trail. The highest BMP implementation cost was reported for the PH II and can be directly related to sensitive zones within the unit (Figure 2.3, Table 2.8). Interestingly, PH II also had the lowest average skidding distance (254 m); however, this did not lower the BMP cost, suggesting that severity and extent of sensitive zones directly impacted the cost of BMP implementation and had little to do with the length of skid trails. No further analysis was done in this regard as the necessary data required for subsequent analysis was not collected as a part of the field study. Despite CC I having the second largest area of sensitive zones and the longest average skidding distance, the BMP implementation cost was found to be lower than PH I (Tables 2.7 and 2.8). This might be due to capturing randomly longer DFCs (skidding distance) during the field data collection. This suggests that for BMP cost analysis, total sampling techniques should be employed in order to capture the actual event compared to random data collection. Furthermore, the field data collectors observed that average skidding distance covered by the skidder on the ground was higher in the PH treatment; however, GPS tracking showed that CC had more distance on the trails (Table 2.7). Among the four treatments, CC II had the lowest cost for BMP implementation which can be directly related to the more sturdy soil profile in the unit. The cost of BMP (handling slash) implementation was influenced by several factors, including machine maneuverability, skidding distance, and the extent and severity of area that required BMP implementation. The machine maneuvering was more efficient for the hockey

stick pattern, characterized by straight skid trails with less abrupt turns. Other studies have found parallel patterns (hockey stick) of skid trails being more productive compared to branching patterns (herring bone) (Gumus & Turk 2016). Additionally, the amount of slash generated during forest operations varies with several factors including harvest system and silvicultural prescriptions (Kizha & Han 2015). BMP implementation costs can be reduced by minimizing skidding activity over sensitive soils. Current technologies, such as water table mapping utilizing LiDAR and computer-based modelling can improve harvest planning by identifying sensitive soils ahead of time. This technology would assist in efficiently designing skid trails and landing locations (Contreras et al. 2016). The results show that BMP implementation can be incorporated into a mainstream harvesting operation without greatly affecting the economic feasibility (Table 2.8). The cost of BMP implementation has been estimated and expressed using different methods and units, respectively (Wear et al. 2013; Kelly et al. 2017). Studies have estimated a wide range of BMP implementation cost on a per hectare basis, Lickwar et al. (1992) (\$64 ha<sup>-1</sup>), Shaffer et al. (1998) (\$30–185 ha<sup>-1</sup>), Sawyers et al. (2012) (\$158 ha<sup>-1</sup>), and Kelly et al. (2017) (\$153 ha<sup>-1</sup>).



**Figure 2.3.** Post-harvest image for the study site: sUAS Near Infrared Orthomosaic layer obtained from Wheatland Lab, University of Maine, Orono; flying altitude 60 m; Ground resolution: 1.39 cm/pixel; Images 1715; Horizontal RMSE: 4.79 cm.

Wear et al. (2013) found that utilizing slash available at the harvesting site was the most cost efficient among different BMP strategies; estimating the cost around \$120 per stream crossing. In a survey done in the Northeastern US, Kelly et al. (2017) reported BMP time ranged between 0 and 37 hours (with a cost up to \$3.88 m<sup>-3</sup>) and varied based on the extent of sensitive area and harvest unit. For this study, the cost of BMP implementation (ranging between \$1.00 and \$3.70 m<sup>-3</sup>) merely contributed between 7–16% of the total operating cost (range: \$14.88–22.94 m<sup>-3</sup>). The alternative for handling forest residue would have been to pile them separately at the landing, which can lead to reduction in the productivity for both the skidder and processor (operational

delay), especially for landings with space limitations. Additionally, laying slash mats on skid trails will facilitate the reduction of site disturbances. The difference in the total operational costs between the Comb PH and Comb CC accounted to 35% (\$8.06 m<sup>-3</sup>) and was a result of the cost required for implementing BMPs to a larger extent in the partially harvested stands. If BMPs were not implemented in these units, excessive machine traffic would have deteriorated the soil profile and the strategies to replenish these sites for future growth will be much more expensive than the cost of the soil reinforcement techniques incurred at present.

#### 2.5.7. Limitations of the study

The cost of operations cannot be solely attributed to the silvicultural treatments, as there were differences in the skid trail distance, severity and extent of sensitive zones between the treatment units. These differences altered the DFCs for some of the operational phases within individual blocks. Additionally, the random sampling technique adopted for the time-motion study led to capturing longer cycles for the PH treatments leading to wide variation in the final operating cost. The variation in soil conditions were not considered for the cost analysis. The skillset of the researchers who took the data for the same operational phases in different prescriptions were divergent which might have resulted in some of the models being not significant. And finally, even though the same machines and operators were used for all the treatments, the skid trail patterns were not standardized.

In conclusion, the study showed there was a slight reduction in the operating cost for CC compared to PH which is in conjunction with the general trends as larger amounts of wood were harvested in the former. The extraction cost nullified the impacts of all other operational phases on the total harvesting cost. The cost of BMP implementation was directly influenced by the



extent and severity of the sensitive zone within the harvest zone, and less impacted by the extraction distance. BMP implementation was found to increase the total extraction cost but can still be mainstreamed to the current operations without significantly affecting the total operational cost. The production economics of silvicultural prescriptions and implementing BMPs are expected to aid forest managers in proper planning, production and protection of the forest stands.

## **CHAPTER 3:**

### **PRODUCTION ECONOMICS: COMPARING HYBRID TREE-LENGTH WITH WHOLE-TREE HARVESTING METHODS**

#### **3.1. Abstract**

Conventional whole-tree harvesting methods involve processing of wood at-landing. Yet, extraction of whole trees to the landing has the potential to negatively impact advance regeneration. For this reason, at-stump processing of logs may be preferred over other harvest methods in stands where natural regeneration is established. However, few studies have evaluated the cost of at-stump processing using a stroke-boom delimber. An experimental study was conducted in central Maine, US in the spring of 2018, to (1) evaluate and compare operational productivity and costs of hybrid tree-length (Hyb TL) and whole-tree (WT) harvesting methods, (2) identify factors influencing productivity of log processing at-stump (i.e., Hyb TL) and at-landing (WT), and (3) calculate best management practice implementation (BMP) costs in WT harvest. Hyb TL and WT treatments were applied in a strip clearcut using a ground-based harvesting system. Logs were processed at-stump in the Hyb TL treatment and at-landing in the WT treatment, using a stroke-boom delimber. Slash was retained only in Hyb TL treatment whereas slash handling occurred only in WT. Time-motion data were recorded for operational phases such as felling, extraction, processing, sorting and loading. Machine rates were calculated to determine productivity and costs of operations. Total cost of Hyb TL (US \$17.01 m<sup>-3</sup>) was found to be lower than WT (\$18.38 m<sup>-3</sup>). Among the operational phases, extraction accounted for the highest costs: 60% in Hyb TL and 65% in WT. Felling was the most productive phase for both treatments (291 m<sup>3</sup> PMH<sup>-1</sup>). Processing cost was found to be lower at-

stump than at-landing (\$2.66 and \$2.73 m<sup>-3</sup>, respectively) which is likely due to fewer logs being handled per cycle at-landing (1.2 logs per turn compared to 1.4 logs per turn at-stump). Sensitivity analysis showed that, a 30 m increase in average in-woods distance travelled by the delimber would increase the processing cost by 41%. Cost of BMP implementation calculated for WT was \$2.25 m<sup>-3</sup> or \$59.2 PMH<sup>-1</sup> (productive machine hour). Results from this study suggest that it is feasible to apply Hyb TL to an industrial harvesting operation keeping in mind the influence of in-woods movement distance on processing costs. Insights from this study should help forest managers, loggers, and researchers to more efficiently plan and execute harvesting operations.

### **3.2. Introduction**

Timber harvesting methods are crucial in achieving a broad spectrum of forest management objectives, including timber and firewood production, wildlife habitat management, forest protection, and aesthetics (Nyland 2016). The strategy of logging has a strong influence on operational costs, productivity (volume produced per hour), revenue generated, and economic feasibility; therefore, efficient and cost-effective timber harvesting is vital for commercial forest management.

Industrial-scale timber harvesting utilizes several silvicultural prescriptions, of which clearcutting, an even-aged regeneration practice, is widely practiced in the US and elsewhere. In the state of Maine, however, clearcutting accounted for only 6.8% of total harvested area as of 2017 (MFS 2018). One of the silvicultural practices related to clearcutting is the retention of unharvested strips between harvested areas, or strip-cutting (Baker et al. 2015). As per the Forestry Rules of Maine (2017), a Category 1 clearcut (2–8 ha) must be separated from other clearcuts by a 76 m wide strip of non-clearcut forestland (MFS 2017). Strip-cutting reduces adverse effects of mechanized logging on wildlife habitat and promotes natural regeneration (Picchio et al. 2018). In mixedwood stands, unharvested strips adjacent to clearcut strips have the potential to modify the species composition of the regenerating stand (Bose et al. 2016). This silvicultural prescription can be executed using whole-tree (WT), cut-to-length (CTL) or tree length (TL) harvesting methods.

In WT, trees are extracted from the stand and processed to market dimensions at the landing. In CTL, trees are processed exclusively at the stump and merchantable logs are brought to the landing. The TL method is intermediate between the CTL and WT methods, wherein logs are

delimbed (partially processed) in-woods, then brought to the landing where a final processing (bucking) might be done to meet market requirements (Hartsough et al. 2001). One of the major advantages of TL over the WT method is that a considerable amount of slash is retained in-woods, and often distributed over the skid trails to protect the soil from machine traffic. Damage to soils may therefore be lower in TL when compared to the WT method (Han et al. 2009). In addition, in mixedwood stands where regeneration relies in part on seedlings established prior to overstory removal, WT has been found to result in greater damage to advance regeneration than other harvesting methods (Waters et al. 2004).

In the WT method, a feller-buncher, skidder, delimber/processor, and slasher are used, where the skidder extracts whole trees that are then processed at the landing using a delimber/processor, bucked, and loaded by a slasher. In the CTL method, harvesting machinery predominantly consists of a harvester and forwarder. Felling, processing, and bucking are carried out by the harvester at the stump. The forwarder then carries the processed logs to the landing and sorts them to facilitate loading. Harvesting equipment for a conventional TL method usually consists of a chainsaw and a cable skidder. A slasher is also often used at the landing for bucking logs. A traditional TL method is exclusively used for small-scale operations (due to functional impairment) and uses relatively obsolete machinery compared to the CTL method (Ponsse 2005). Harvesting operations using dilapidated (seasoned) equipment may lower initial capital investment but increase risk of mechanical delays, which ultimately reduces productivity. In contrast, operating newer and advanced machinery is usually associated with higher productivity, but often corresponds to higher initial capital (Regula et al. 2018).

In general, 80% of recent timber production in Maine comes from WT method, and TL accounted for about 7% of the production (Leon & Benjamin 2013). Limited studies have been done on the

cost and productivity of the TL harvesting method. Comparison of TL and WT methods have shown that the extraction cost per cubic meter of timber in WT was almost double that of TL (\$0.32 and \$0.17 m<sup>-3</sup>, respectively) (Feghi 1987). Zundel & Lebel (1992) also pointed out that, the cost per cubic meter of wood harvested for the WT method was 4% higher than that of TL. Employing a stroke-boom delimber inside the harvest unit is a unique harvesting method practiced in the northeastern US. Natural regeneration, often present at the time of harvest, is the principal form of stand re-establishment in this region (Brissette 1996). This harvesting method, generally referred to as hybrid TL method (Hyb TL), ensures less damage to the regeneration during extraction of the wood compared to WT and is believed to be more productive than the conventional TL using chainsaws. Unlike the conventional TL method, the Hyb TL method is employed in industrial-level harvesting operations. Studies have shown that shade provided by slash such as that left at the site during Hyb TL favors natural regeneration of softwoods (Rinaldi 1970; Verme & Johnston 1986). Productivity of a stroke-boom delimber operating at the landing ranged widely between 10–108 m<sup>3</sup> PMH<sup>-1</sup> (Andersson & Evans 1996; Hiesl 2013; Kizha & Han 2016). However, production economics of in-woods delimber operations at the stump have rarely been analyzed.

### 3.2.1. BMP implementation

A major concern for any mechanized forestry operation is site disturbance that results in degradation of soil and stand quality. Although site disturbances from forestry practices cannot be eliminated, damages can be mitigated through careful implementation of best management practices (BMPs) during forest operations (Han 2007). Maintaining slash on trails is a common BMP employed throughout the United States. Covering the machine trails with slash and ensuring its continuity on the trails has been found to limit the extent of soil disturbance by

reducing the probability of soil compaction and rutting (Han et al. 2006; Han et al. 2009). Previous studies have proposed that BMP implementation can be incorporated into mainstream harvesting operations without considerably affecting the harvesting costs (Kelly et al. 2017; Soman et al. 2019).

Production economics of a Hyb TL method have not been scientifically quantified; the data available for the costs and productivity are primarily anecdotal. Hence, there is a need to analyze the various operational aspects of the Hyb TL and compare it to other widely practiced harvesting methods. The main objectives of this study were to (1) evaluate and compare the operational productivity and costs of a hybrid tree-length (Hyb TL) and whole-tree (WT) harvesting methods, (2) identify factors influencing the processing (delimbing) costs and productivity at the stump and landing, and (3) calculate the cost of implementing BMPs.

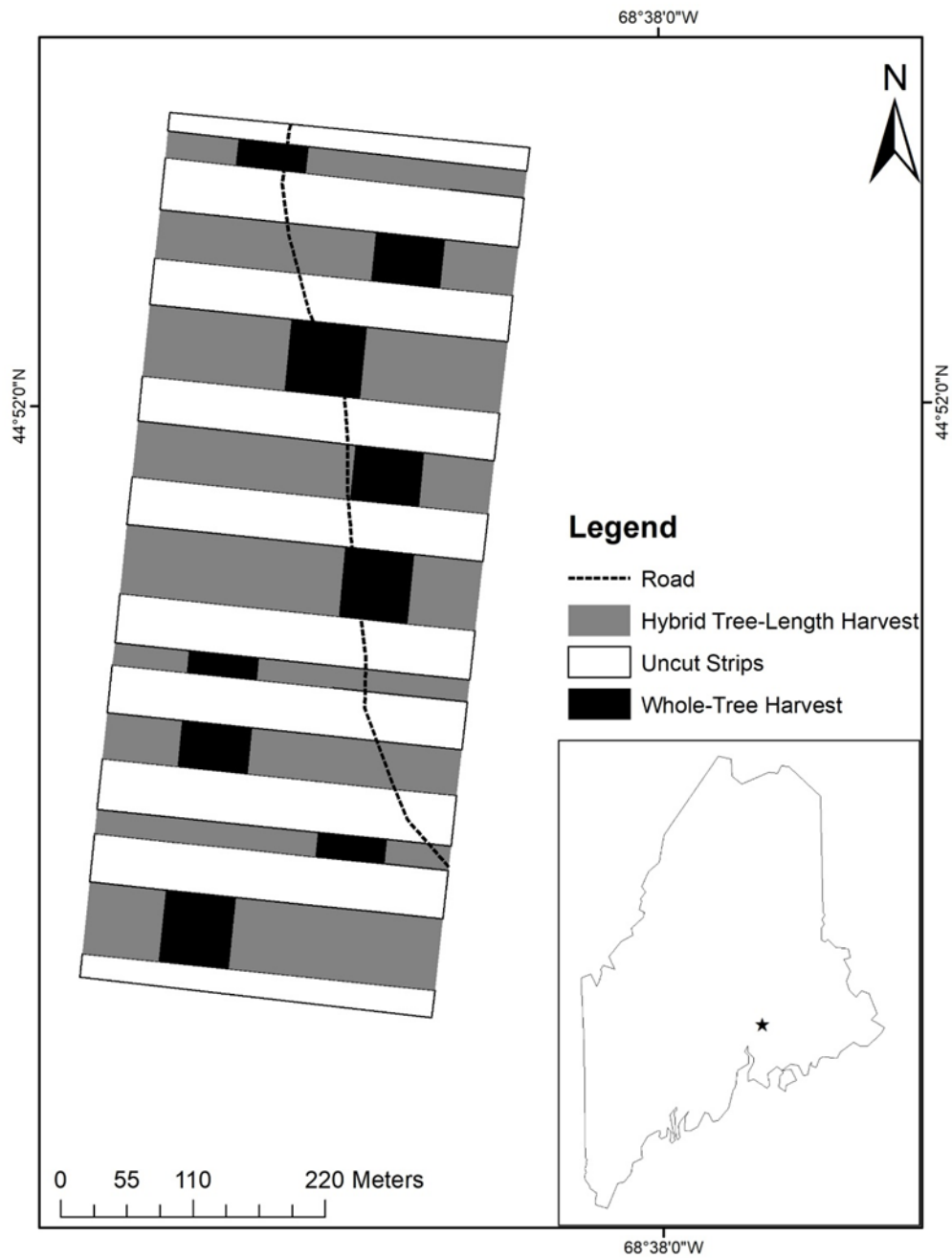
### **3.3. Materials and Methods**

#### **3.3.1. Study Area**

The study was conducted in a 21.6 ha stand managed by the U.S. Forest Service at the Penobscot Experimental Forest (PEF) in Bradley, Maine, US (44° 51' 56.754'' N, 68° 38' 12.181'' W) (Figure 3.1). The stand had a gentle slope (<15%), with the region experiencing a mean annual temperature of 6.6 °C, annual precipitation of 107 cm, and heavy snowfall with an annual average of 168 cm (NOAA 2019). The elevation of the site was about 200 m above mean sea level. Soil types in the site are of glacial-till and marine sediment parent material. Soil type and drainage of the site varied from north to south with moderately well-drained Howland loams dominating the northern portion whereas, poorly-drained Monarda-Burnham complex and Scantic silt loams were dominant in the southern portion (Munoz 2017). This variation in soil

profile and drainage is a crucial factor contributing to the wide variation in species composition throughout the stand. Dominant tree species present in the site were balsam fir (*Abies balsamea* (L.) Mill.), red maple (*Acer rubrum* L.), red spruce (*Picea rubens* Sarg.), black spruce (*Picea mariana* Mill.), eastern white pine (*Pinus strobus* L.), quaking (*Populus tremuloides* Michx.), and big-tooth aspen (*Populus grandidentata* Michx.). Species present in lower proportions were northern white-cedar (*Thuja occidentalis* L.), eastern hemlock (*Tsuga canadensis* (L.) Carrière), red oak (*Quercus rubra* L.), white spruce (*Picea glauca* (Moench) Voss), white ash (*Fraxinus americana* L.), gray birch (*Betula populifolia* Marsh.) and paper birch (*Betula papyrifera* Marsh.).





**Figure 3.1.** Clear-cut strips showing extent of hybrid tree-length (Hyb TL) and whole-tree (WT) harvest treatments.

Out of the 21.6 ha, 10.8 ha were harvested as part of this study. Hyb TL harvest was conducted in 8.7 ha and WT treatment accounted for 2.1 ha. There were nine clearcut strips oriented east-

west, with the strips at the ends adjacent to 20 m wide buffers and other strips separated by 40 m wide buffers. The width of the strips were 20, 40, and 60 m, which were each replicated three times.

### 3.3.2. Stand Inventory

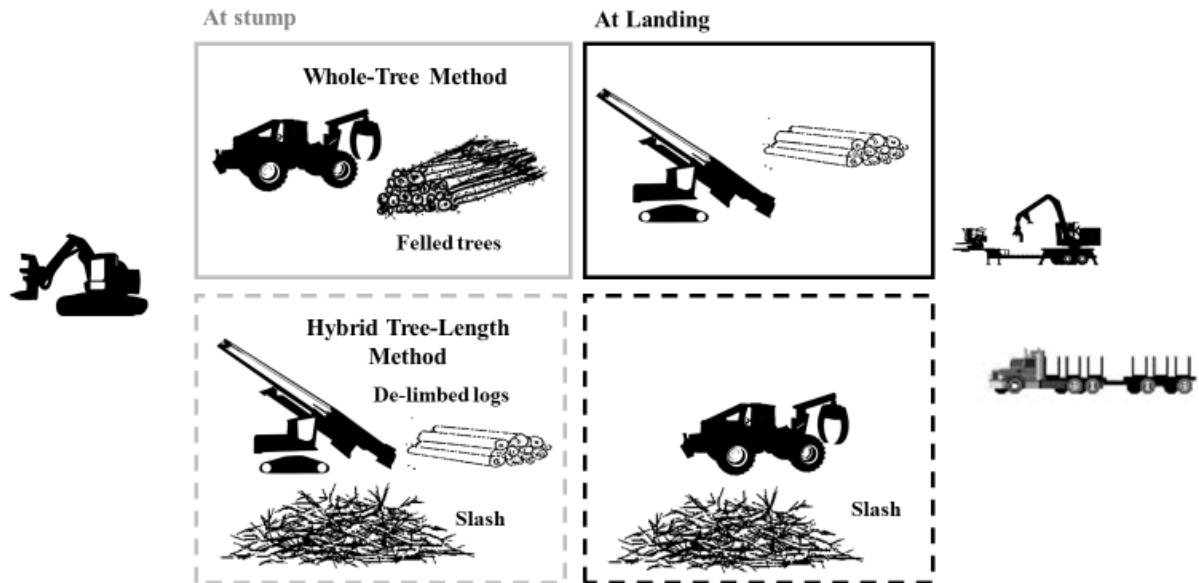
Stand inventory was conducted using 19 fixed-area plots with sizes of 0.08 ha and 0.02 ha in the 10.8 ha study area. Out of the 19 plots, 12 plots (of 0.08 ha each) were in the Hyb TL treatment and 6 plots (of 0.08 ha each) were in the WT. A single plot of 0.02 ha was present in WT treatment. The inventory was conducted at 22% sampling intensity. All trees  $\geq 11.4$  cm of DBH were inventoried.

### 3.3.3. Harvesting Operation and Treatment

The last recorded harvest at this site was a strip clearcut in 1964-65 using chainsaws and a tractor. The harvest followed similar in-woods processing and WT extraction treatments (Bjorkbom & Frank 1968). The current harvest was done in February and March of 2018, during which there were two snow storms (45–60 cm of snowfall).

Each strip was designated either a Hyb TL or WT treatment (Figure 3.1). The primary difference between the methods occurred during the processing phase. In Hyb TL, at-stump processing was done by deploying a stroke-boom delimber inside the harvest unit and processed wood was extracted to the landing. In the case of WT, whole trees were extracted using a skidder and processed at the landing (Figure 3.2). Another difference was that the slash (i.e., harvest residues such as limbs, offshoots, and broken logs) were retained at the site in Hyb TL, whereas, for the WT treatment, the harvest residues were taken back from the landing and deposited in the Hyb

TL treatment areas. The same machines and crew operated for all the treatments. The experience of the crew ranged from 5 to 25 years.



**Figure 3.2.** Description of operational components at the stump and landing for the hybrid tree-length (Hyb TL) and whole-tree (WT) treatments. In WT, the skidder brings the unprocessed logs to the landing and processing is done at landing and in Hyb TL processing is done at the stump and the skidder carries the delimbed logs to the landing.

#### 3.3.4. Data Collection

The harvesting operation consisted of different operational phases namely, felling, processing, extraction, sorting and loading. Time-motion data were recorded for different tasks involved in each of the operational phases. The predictor variables expected to influence the efficiency of operations were also recorded (Table 3.1).

**Table 3.1.** Cycle elements and predictor variables recorded for each operational phase.

Operational phase	Cycle elements	Recorded predictor variable(s)
Felling	Travel empty	Trees cut per cycle
	Cutting	Tree species
	Bunching	Butt-end diameters (cm)
	Scattering <sup>1</sup>	Distance between trees (m)
	In-woods movement	Distance to bunch (m)
Processing	Grappling	Distance of in-woods movement (m)
	Processing sawlogs	Tree species
	Decking sawlogs	Butt-end diameters (cm)
	Piling biomass	Number of cuts
		Number of logs handled per turn
Extraction	Travel empty	Distance to the bunch (m)
	Positioning	Loaded distance (m)
	Grappling	Number of pieces
	Re-grappling	Diameter per piece (cm)
	Travel loaded	Distance traveled for picking up slash (m)
	Dropping grapple	
	Picking slash	
	Handling slash	
Loading and sorting	Swing empty	Diameter of logs (cm)
	Grapple	Number of logs handled per turn
	Swing loaded	
	Bucking <sup>2</sup>	
	Sorting	
	Loading	

<sup>1</sup>Scattering was done while laying the skid trails during the initial operations of the feller-buncher<sup>2</sup>Bucking was done for logs including logs from the hybrid tree-length and whole-tree treatment.

The various operational phases and the variables collected were:

#### 3.3.4.1. Felling

The feller-buncher (John Deere 753G) started by laying trails, which involved felling and piling trees on the designated skid trails. Felling operation started from the back of the stand and progressed towards the road. Felling cycle began as the machine traveled empty to a tree (travel empty) followed by cutting trees (cutting). The cycle ended as the head of the feller-buncher clutched trees while rotating and stacked into a new or existing pile/ bunch (bunching). The time taken for these three cycle elements (travel empty, cutting, and bunching) constituted the delay free cycle time (DFC). Distance moved by the machine for every cycle element was visually estimated; this was facilitated by setting markers at fixed intervals. The operation phases were decoupled with the feller-buncher operating one week prior to the skidder.

#### 3.3.4.2. Extraction

Two grapple skidders (John Deere 748H) were employed in this operational phase, which brought unprocessed trees from the WT treatment stands and delimbed logs from the Hyb TL to the landing (Figure 3.2). Extraction DFC started when the machine traveled empty from landing to the unit (travel empty). After arriving near the bunch, the skidder positioned itself for grappling the trees/logs (positioning). Grappling initiated as the skidder began grappling the bunch; if a grapple was dropped and then re-picked, it was considered re-grappling. Grappling ended as the machine started skidding the bunch back to the landing (travel loaded). Travel loaded cycle element ended and dropping grapple cycle element started as the skidder dropped the bunch at the landing. Distance travelled, diameter (at butt end), and the number of pieces (trees or logs) skidded during each cycle were recorded based on ocular assessment.

#### 3.3.4.3. BMP Implementation

Following the prescription, slash was only handled for the WT treatment, which resulted in two additional cycle components to the DFC for the WT treatment: picking up slash (at landing) and handling slash (in unit). As the skidder moved back to the unit from the landing, it carried slash generated during the processing phase and placed the slash on skid trails, especially on sensitive spots. BMP implementation time was calculated by summing the time required for each of these additional cycle components.

#### 3.3.4.4. Processing

A stroke-boom delimber (John Deere 200 LC) was used for processing. DFC initiated when the processing head swung empty to the pile (swing empty). Swing empty cycle element was followed by grappling the tree (grappling), swinging loaded, and processing the tree. The cycle ended when the log was placed in a deck (decking). For the Hyb TL treatment, the delimber had an additional cycle element: in-woods movement, as the machine was mobilized inside the unit. When the delimber was at the landing, it also decked the processed logs brought in by the skidder from the Hyb TL treatment along with logs processed at landing (WT). Processing began prior to the extraction phase in the Hyb TL treatment areas. Predictor variables expected to influence the DFC, which include the distance travelled in-woods, species handled (softwood or hardwood), number of logs handled per cycle, butt end diameter of logs, and number of cuts made per cycle, were visually estimated and recorded.

#### 3.3.4.5. Sorting and Loading

Sorting and loading were done using a slasher-loader (Serco 300) for both harvesting treatments combined. Merchantable products for this study consisted of sawlogs and pulpwood. Sawlogs for each sort were bucked into appropriate market dimensions. Sorting and loading had the same

DFC components. The cycle began when the machine swung empty to the deck of logs (swing empty), followed by grappling and swing loaded, then culminated when the log was placed in separate log piles (sorting), or on the log truck (loading). For the cycles with bucking, there was an additional operational component of cutting the logs to market dimensions in between swinging loaded and sorting of logs element.

#### 3.4.5. Machine Rate Calculation

Average DFC for all cycle components were calculated for both treatments. Predictor variables expected to affect DFC were recorded along with the time components (Table 3.1). Mechanical, operational, and personal delays were recorded to better understand the factors that influenced productivity (Kizha & Han 2016). The operational costs for the two harvesting treatments were evaluated as cumulative productive machine cost incurred during the performance of the various operational phases (an operational phase was considered as any activity that would change the position or form of the wood).

Owning and operating costs of the machines such as purchase price, salvage value, economic life, utilization rate for the machines, and salary and fringe for the logging crew were obtained from the company that owned and operated the machines (Table 3.2). Fuel price was set at \$0.72 L<sup>-1</sup>, which reflected the market price during the time of operation. Hourly machine costs in US dollars per scheduled machine hour (\$ SMH<sup>-1</sup>) were calculated using standard machine rate calculation methods as per Miyata (1980), which were later used to calculate the cost of productive machine hours (\$ PMH<sup>-1</sup>). Scale tickets for the wood products were obtained from the forest management company.

**Table 3.2.** Costs (US\$) related to the machinery used for harvesting and skid trail establishment. These values do not include support vehicles such as fuel trucks and personal vehicles.

Element	Felling	Extraction	Processing	Sorting & Loading
Make & Model	John Deere 753G, 2008	John Deere 748H, 2011	John Deere 200 LC, 2004	Serco 300, 2008
Purchase price (\$)	275,000	320,000	345,000	200,000
Variable and operating cost (\$)	37.36	53.10	76.85	28.03
Salvage value (\$)	52,250	73,600	34,500	50,000
Labor cost (\$PMH <sup>-1</sup> )	42.86	43.08	35.00	39.75
Fuel use (L PMH <sup>-1</sup> )	18.93	22.71	22.71	22.71
Utilization (%)	70	65	80	80
Machine rate (\$PMH <sup>-1</sup> )	130.49	159.60	175.10	103.40

Fuel cost was set at \$0.72 L<sup>-1</sup> as per the market conditions during harvest time. Machine rate per productive machine hours (\$ PMH<sup>-1</sup>) was calculated based on 2200 SMH (schedule machine hours)/year, 10% interest, and 3% insurance (provided by the company that operated and owned the machines). Same machines and operators were employed for both hybrid tree-length and whole-tree treatments.

#### 3.4.6. Statistical Analysis

A two tailed *t*-test was performed ( $p = 0.05$ ) to analyze variability in DBH of trees among treatments. Boxplots were created for the feller-buncher, delimber and skidder (sorting and loading were not treatment-specific) for both the treatments for analyzing the trends in DFC. DFC values were analyzed for outliers using a 95% confidence interval. Regression models were developed in IBM SPSS 24 statistical software. Dummy variables were used to represent species. Models were selected based on two criteria: fulfilment of the assumption of normality and higher adjusted  $R^2$  values. Multi-collinearity was tested using a tolerance value greater than 0.1 and variance inflation factor (VIF) less than 10 (Soman et al. 2019).



Machine rate calculations were done by using standardized variables for the harvesting treatments (Kizha & Han 2016). Standardized variable comparison helped to illustrate differences in cost and productivity due to the harvesting method (treatment) without accounting for variance in stand and operational conditions (Kizha & Han 2015). Scaling of logs was done during the harvesting and the parameters recorded were small-end, large-end diameters (cm) and length (m) of the logs from different decks.

#### 3.4.7. Sensitivity Analysis

Sensitivity analysis was conducted to analyze the trends in processing costs with respect to in-woods movement distance of the delimber. The fluctuations of in-woods movement distance had values ranging from 0 to 91 m. Initially, a linear regression model was developed for change in DFC with in-woods distance. Then, in-woods distance values from 0 to 180 m were substituted in the regression equation to understand the sensitivity of DFC of the stroke-boom delimber towards in-woods movement distance. Based on the change in DFC, corresponding values of operational costs were estimated to determine the increase in processing cost with respect to in-woods movement.

### 3.4. Results

#### 3.4.1. Stand Inventory

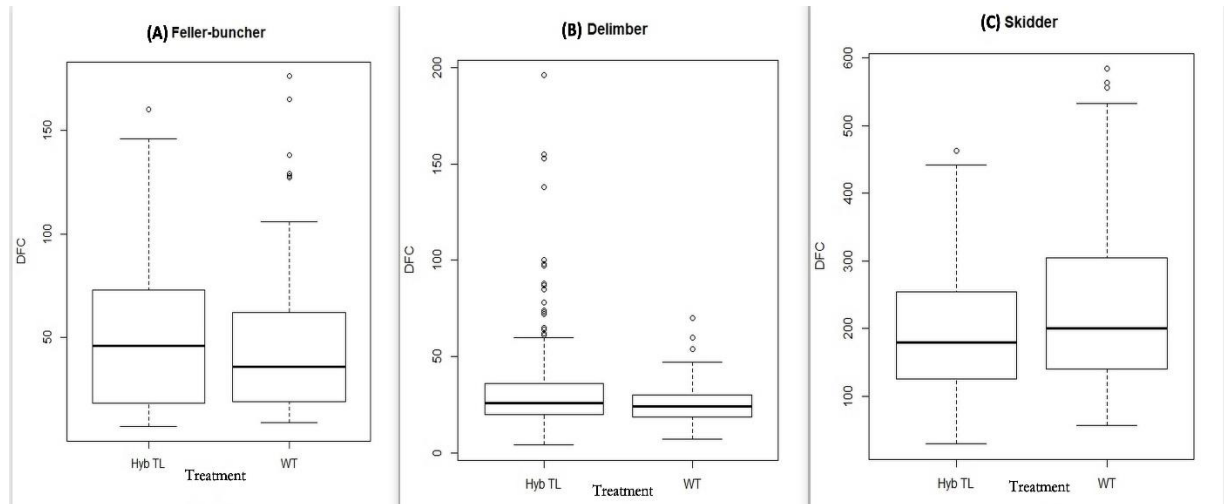
Results from the *t*-test showed that there was no significant difference between the treatment stands in terms of DBH ( $p = 0.69$ ). Stem density and basal area  $\text{ha}^{-1}$  were calculated for both treatments separately (Table 3.3).

**Table 3.3.** Stand attributes of areas under hybrid tree-length (Hyb TL) and whole-tree (WT) harvesting treatments at 22% sampling intensity and considering only trees of diameter at breast height  $\geq 11.4$  cm.

Stand attributes	Hyb TL	WT
Area (ha)	8.7	2.1
Number of plots	12	7
Stem density (trees ha <sup>-1</sup> )	1071	1149
Total basal area (m <sup>2</sup> ha <sup>-1</sup> )	24.0	27.2

### 3.4.2. Harvesting Operation

DFC was calculated for all the operational phases and average values of DFC were estimated with standard error (Figure 3.3; Table 3.4).



**Figure 3.3.** Boxplots comparing the trends in delay free cycle time (DFC) for different machines for hybrid tree-length (Hyb TL) and whole-tree (WT) treatments: (A) Feller-buncher; (B) Delimber; and (C) Skidder.

**Table 3.4.** Statistics of the delay free cycle times (DFCs in secs) of the different operational phases for hybrid tree-length (Hyb TL) and whole-tree (WT) harvesting methods.

Operational phase	Prescription	Mean	Standard error
Felling	Laying Trails	72.74	5.14
	Hyb TL	53.44	3.76
	WT	45.60	3.40
Processing	Hyb TL	33.65	1.67
	WT	25.10	0.98
Extraction	Hyb TL	193.84	9.69
	WT	247.83	20.01
Sorting	N/A*	30.20	1.19
Loading	N/A*	60.44	4.41

\*Not applicable as the operation was not treatment-specific and was combined for both treatments

The total cost of operations from stump to truck was estimated to be \$17.01 and \$18.38 m<sup>-3</sup> for the Hyb TL and WT treatments, respectively (Table 3.5).

**Table 3.5.** Cost of operating (in US\$ m<sup>-3</sup>) and productivity (m<sup>3</sup> PMH<sup>-1</sup>) of the different phases of the operation in hybrid tree-length (Hyb TL) and whole-tree (WT) treatments.

Operational phase	Cost		Percentage difference in cost <sup>a</sup>	Productivity	
	Hyb TL	WT		Hyb TL	WT
Felling <sup>b</sup>	2.13	1.65	- 22.5	264	317
Processing	2.66	2.73	+ 2.6	66	64
Extraction <sup>c</sup>	10.17	11.96	+ 17.6	31	26
Sorting	0.96	0.96	N/A <sup>e</sup>	108	108
Loading <sup>d</sup>	1.09	1.09	N/A	95	95
Total	17.01	18.38		564	610

<sup>a</sup> Percentage difference in cost is calculated based on Hyb TL treatment; “+” and “-” indicate higher and lower cost of WT compared to Hyb TL, respectively.

<sup>b</sup> Cost and productivity of laying trails was included to the felling phase for both treatments.

<sup>c</sup> Cost of extraction included cost of operating two skidders.

<sup>d</sup> Loading cost was similar for both treatments as the piles were combined at the landing

<sup>e</sup> Percentage difference in cost is not applicable for sorting and loading as the operation was combined for both treatments.

Adjusted  $R^2$  values for the DFCs modelled were between 0.18 and 0.75 (Table 3.6). According to the scale tickets, a total of 1,457 metric tons of wood (1,342 metric tons of pulpwood and 115 metric tons of sawlogs) were harvested in total, for both treatments combined. Due to space restriction at the landing, the logs were piled and sorted together, irrespective of treatment, based on their market dimensions. The amounts of wood harvested from each treatment separately were not available.

**Table 3.6.** Regression models developed for predicting delay free cycle time (DFC) in minutes using standardized comparison. All units are in cm for diameter and in m for distance. Dummy variables were used for the species (i.e., hardwood or softwood).

Phases	Treatments	Number of DFCs recorded	Adjusted $R^2$	Standardized models predicting DFC
<b>Felling</b>	Laying of trails	99	0.18	$\text{Log DFC} = 1.247 + 0.008 (\text{Distance between trees}) + 0.036 (\text{Number of trees cut/cycle})$
	Hyb TL	104	0.19	$\text{Log DFC} = 1.053 + 0.127 (\text{Species})$
	WT	106	0.34	$\text{Log DFC} = 1.193 + 0.033 (\text{Distance between trees}) + 0.005 (\text{Distance to bunch}) + 0.036 (\text{Number of trees cut/cycle})$
<b>Processing</b>	Hyb TL	238	0.26	$\text{DFC} = 24.323 + 0.369 (\text{In-woods distance})$
	WT	100	0.50	$\text{DFC} = -10.031 + 1.611 (\text{Average diameter/cycle}) + 17.882 (\text{Number of cuts}) + 4.742 (\text{Number of logs/cycle})$
<b>Skidder</b>	Hyb TL	104	0.75	$\text{Log DFC} = 1.848 + 0.001 (\text{Travel empty distance}) + 0.001 (\text{Travel loaded distance}) + 0.002 (\text{Positioning distance})$
	WT	53		Model not Significant

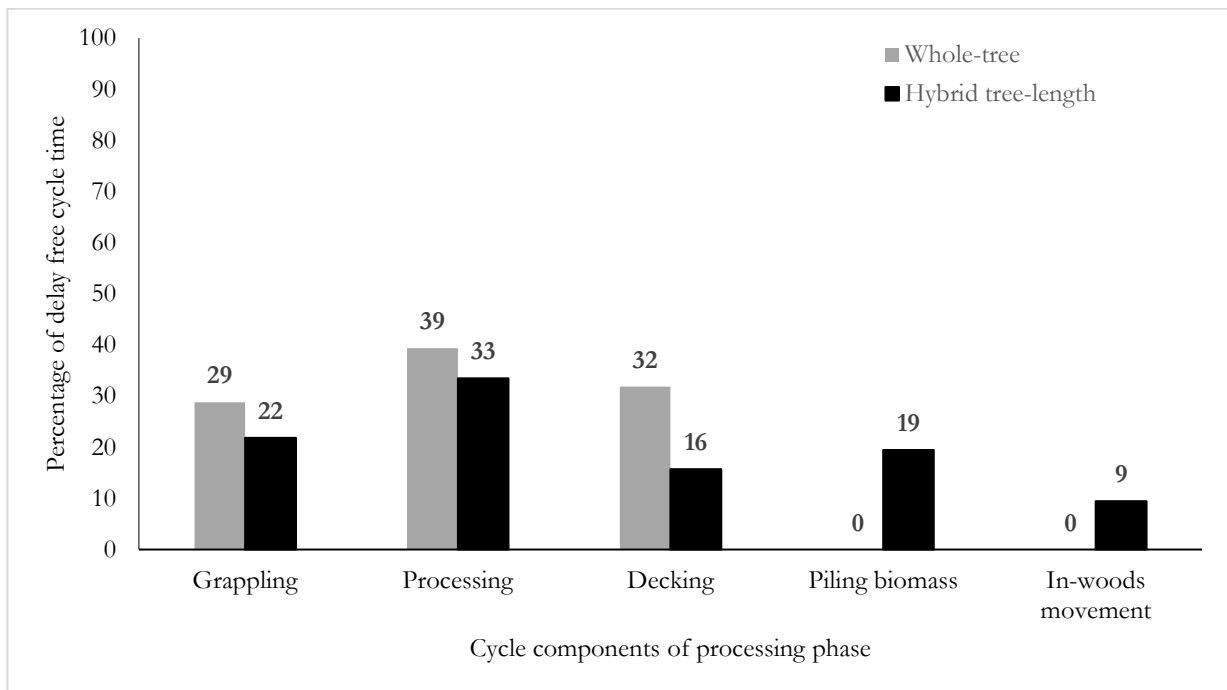
\*Hyb TL is hybrid tree-length treatment, WT is whole-tree treatment, Log DFC is the log to the base 10 of DFC.

#### 3.4.2.1. Felling

A total of 309 DFCs were recorded for the feller-buncher. Felling was the most productive operational phase for both Hyb TL and WT treatments (Table 3.5). Average DFC for Hyb TL was found to be 8 sec more than WT. The cost of felling operations for Hyb TL and WT treatments were estimated to be \$2.13 and \$1.65 m<sup>-3</sup>, respectively. While laying trails, the time taken to scatter slash accounted for majority of the DFC time (43%). The cost of laying trails (\$0.78 m<sup>-3</sup>) was included in the felling costs for both treatments.

#### 3.4.2.2. Processing

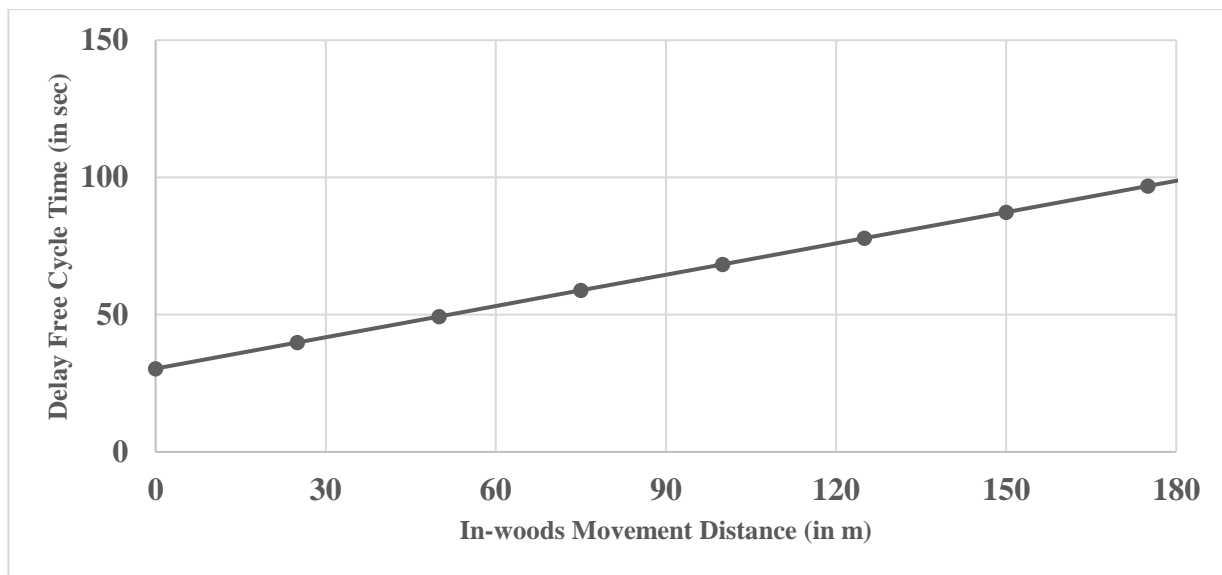
For accomplishing the second objective, a total of 338 processing cycles were recorded for both treatments. On average in Hyb TL, processing (delimbing) time had the highest contribution to the DFC (33%). In-woods movement time (for Hyb TL), only contributed 9% to the DFC (Figure 3.4).



**Figure 3.4.** Time taken for cycle components of the delimber expressed as a percentage (%) of the delay free cycle time for both hybrid tree-length and whole-tree methods. Where, grappling is picking up logs from the feller-buncher sort; processing is delimbing logs; decking logs is placing logs in bunches for facilitating extraction; piling biomass is handling harvest residues; in-woods movement is moving from one bunch (made by the feller-buncher) to another.

The DFC for the Hyb TL treatment derived from the standardized model was found to be 8% higher than that of the WT (28 and 26 sec, respectively). Despite this, the cost for Hyb TL was found to be slightly lower than that of WT (\$2.66 and \$2.73 m<sup>-3</sup>, respectively). Processing costs accounted for 16 and 15% of the total operational cost in Hyb TL and WT treatments, respectively. Productivity was similar for Hyb TL and WT and averaged 65 m<sup>3</sup> PMH<sup>-1</sup>. The linear

regression model developed for change in DFC with in-woods movement distance had a slope of  $y = 0.38x + 30.36$  with an  $R^2$  value of 0.27. A graph was developed based on the values obtained from the equation to show the sensitivity of in-woods distance on DFC (Figure 3.5).



**Figure 3.5.** Graph showing the trend in total delay free cycle time (secs) corresponding to increasing in-woods movement distance (m).

#### 3.4.2.3. Extraction

A total of 156 cycles were recorded for both treatments. The final extraction cost included costs for both the skidders used. Regression models developed for Hyb TL treatment showed that travel empty, travel loaded, and positioning distance significantly influenced the DFC ( $p < 0.05$ ). The models developed for extraction DFC for WT were not found to be statistically significant (Adjusted  $R^2 < 0.10$ ,  $p > 0.05$ ). Extraction was the most expensive phase, accounting for 60 and 65% of the total operating costs in Hyb TL and WT treatments, respectively. Volume used to calculate the cost in WT was obtained from the scaling data for merchantable logs, despite the fact that whole trees have higher volume than processed logs. This assumption was based on the idea that harvest residues from the tree such as branches and tree tops received a free-ride to the landing, as it was not merchandized.

#### 3.4.2.4. BMP Implementation

On average, time to implement BMPs in the WT stands was estimated to be 95 sec per cycle, costing \$2.25 m<sup>-3</sup> or \$59.2 PMH<sup>-1</sup> (productive machine hour). Handling slash was the major time component in BMP implementation contributing about 66% to the BMP DFC.

#### 3.4.2.5. Sorting

Sorting was combined for the Hyb TL and WT, and 77 DFCs were recorded. For this reason, regression analysis was not done for the treatments, and the average DFC of 30 sec was used for calculating the operational cost for both treatments.

#### 3.4.2.6. Loading

Loading data were collected for 62 cycles. Loading cycle had an average DFC of 60 sec, and the average time to load a truck was estimated to be 26 min. Similar to sorting, cost and productivity of loading were calculated together for both treatments because the logs from both treatments were piled together at the landing for trucking.

### 3.5. Discussion

During felling, laying of trails had the highest value for mean DFC ( $72.74 \pm 5.14$  sec). This coincides with the results from an earlier study conducted in the region that had similar results of an increased cycle time while operating in trails compared to cutting inside the stands (Hiesl 2013). Regression models showed that the number of trees cut per cycle was a significant factor influencing the productivity of the feller-buncher during the trail laying phase and felling in the WT treatment (Table 3.6). Distance to bunch and the size of trees (average butt-end diameter of trees handled per cycle) were common factors that influence the productivity of felling (Kluender et al. 1998; Li et al. 2006; Kizha & Han 2016). However, these factors were not found to be



significant ( $p > 0.05$ ) in the model of trail laying. This deviation from the general trend could be attributed to the nature of operation as trees were cut and dropped on trails, rather than being bunched for facilitating upcoming tasks. In Hyb TL, species (whether hardwood or softwood) was the only significant factor influencing DFC, which may be because of the contrast in species composition in the stand. Studies have shown that tree form indicators (such as branching patterns and crown width) which vary between softwoods and hardwoods, influences the felling time (Verme & Johnston 1986; Dodson et al. 2006; Kizha & Han 2016). Feller-buncher productivity obtained from this study (average  $291 \text{ m}^3 \text{ PMH}^{-1}$ ) was relatively high compared to other similar studies, which reported values in the range of 22 to  $117 \text{ m}^3 \text{ PMH}^{-1}$  (Andersson & Evans 1996; Hiesl 2013). A possible reason for this difference is that the relatively small harvested area in the present study facilitated better maneuverability of the feller-buncher between harvest units.

Average productivity of the stroke-boom delimber ( $65 \text{ m}^3 \text{ PMH}^{-1}$ ) found in this study was almost double the productivity for similar studies conducted in Maine (10 to  $30 \text{ m}^3 \text{ PMH}^{-1}$ ) (Hiesl 2013) but is in accordance with the studies from other regions ( $48$  to  $60 \text{ m}^3 \text{ PMH}^{-1}$ ) (Andersson & Evans 1996). In Hyb TL, distance moved in-woods was the only significant factor ( $p < 0.05$ ) that influenced DFC, suggesting that the hybrid harvesting method can alter productivity of the processing phase. It was estimated that a 30 m increase of in-woods distance could increase cost of operations by 41% (Figure 3.5). However, difference in DFC between in-woods and at-landing processing was minimal (2.1 sec). Interestingly, cost of operations for Hyb TL treatment was slightly lower than WT ( $\$0.07 \text{ m}^{-3}$ ), despite average DFC being higher for the former. This anomaly might be due to higher mean number of logs handled per cycle in Hyb TL (1.4 logs per turn) compared to WT (1.2 logs per turn), resulting in a greater volume per turn (0.63 and 0.59

m<sup>3</sup>, respectively). A possible reason for the lower volume handled in WT was the intense snowfall (40-65 cm) during the processing phase of that treatment. The snow event was a confounding variable, which might have influenced the cost of operations, because processing in Hyb TL treatment was done prior to the snowfall and WT treatment was processed after the snowfall. Nevertheless, these findings suggest that, as at-stump processing cost was only 16% of the total operating costs, Hyb TL can be incorporated into a regular harvesting operation without considerably affecting the overall cost of operations. However, as a result of in-woods movement, the chances of wear and tear on the tracts of the processor (a significant component influencing the economic life of the machine) would be comparatively higher, thereby increasing the fixed and operating costs (Madden 2018). That analysis is outside the scope of the present study and warrants further investigation.

Extraction was the decisive factor in determining the overall costs of the operations. The average extraction distance was estimated to be 63 and 44 m for Hyb TL and WT, respectively. Generally, average large-end diameter of trees and average number of pieces handled per cycle, along with the extraction distance, are the factors that influence productivity (Visser et al. 2003). Due to large snow accumulation on the bunch, the operator had difficulty in positioning the skidder to grapple the bunch efficiently, which explains the influence of positioning distance. Potential reasons for these results might be the comparatively lower number of extraction cycles compared to Hyb TL (53 and 103 cycles, respectively), which can be attributed to smaller area harvested in the WT treatment (2.13 ha). Extraction productivity results obtained in this study were comparable to previous studies, which ranged between 6 and 45 m<sup>3</sup> PMH<sup>-1</sup> (Lanford & Stokes 1996; Hiesl 2015).

### 3.5.1. BMP Implementation

Soman et al. (2019) reported that the cost of BMP implementation can be a function of the severity and extent of sensitive soil within the harvested stand. As this operation was done during on frozen ground with snow cover, these parameters could not be captured. The cost of BMP implementation was found to be around 12% of the total cost of operations for the WT treatment. BMP implementation costs can be reported in different formats including labor cost involved, cost of materials and structure, cost in terms of PMH<sup>-1</sup>, cost per unit area of harvested stand, and as a percentage of unit volume of wood harvested (Table 3.7). BMP implementation costs reported in the study fall within the range of values reported by similar prior studies.

**Table 3.7.** Studies conducted on costs of forestry best management practices (BMP) in the United States over the years.

Study	Geographic region	BMP costs (in US \$)
Lickwar et al. (1992)	Southeastern States	64 ha <sup>-1</sup>
Shaffer et al. (1998)	Virginia	30–185 ha <sup>-1</sup>
Sawyers et al. (2012)	Virginia	158 ha <sup>-1</sup>
Wear et al. (2013)	Virginia	120/Stream crossing
Kelly et al. (2017)	Northeastern States	3.88 m <sup>-3</sup>
Soman et al. (2019)	Maine	1.1–3.7 m <sup>-3</sup> or 10–52 PMH <sup>-1</sup>

\*'ha' corresponds to hectare, 'm' corresponds to meter and PMH corresponds to productive machine hour

### 3.5.2. Management Implications

From a managerial viewpoint, a conventional WT harvest is easier to execute than the Hyb TL treatment. In light of the need to move the delimber within the harvest unit, Hyb TL treatment should be carefully executed and demand intense planning such as appropriate skid trail patterns, avoiding areas susceptible to soil disturbance, and proper installation of the landing area. From an operational perspective, at-stump processing can be expected to decrease the machine life of

the delimber. However, the Hyb TL harvesting method is likely to minimize residual seedling damage relative to the WT method of harvesting which causes damage to the understory vegetation (Waters et al. 2004; Ranius et al. 2018). In addition, the Hyb TL treatment ensures better retention of deadwood biomass within the stand compared to WT. In addition to non-timber benefits, slash retention creates cover and low shade that may help established seedlings by moderating microclimatic extremes and reducing competition from non-tree vegetation (Proe et al. 2001). In contrast, the WT method can foster understory vegetation and increase competition experienced by seedlings of desired growing stock (Mann et al. 1988).

In the WT method, the extraction of unprocessed trees to the landing may result in higher site disturbances, this has led to concerns about long-term negative impacts on soil quality and site productivity (Reynolds & Stevens 1998; Merino et al. 2005; Walmsley et al. 2009). Additionally, it has been observed in the field that extraction in WT could cause damage to the trees being transported, resulting in loss of merchantable volume of wood. Another advantage of Hyb TL over WT is the handling of harvest residue at the stump; this becomes particularly critical in log landings with limited space. In the present study, the contractor said he would need to skid back the harvest residues generated during WT processing, in order to keep the landing cleared for bringing in wood, even if it was not prescribed.

Even though the site was poorly drained in the southern portion, no notable soil disturbances were observed. The thick slash layer in the Hyb TL treatment, along with 30–40 cm of snow, shielded the soil and protected it from the impact of the machine passes which is consistent with the findings from an earlier study (Agherkakli et al. 2014). This would likely help in reducing post-harvest site-preparation costs such as rehabilitation of heavily compacted soils (Han 2007). Snow, as discussed earlier, could reduce the efficiency of operations, but it might also, mitigate

soil disturbances. Therefore, winter harvesting can be employed as a feasible strategy for harvesting on poorly drained sites to reduce the risk of post-harvest site quality deterioration.

### 3.5.3. Limitations of the Study

The study was done on an experimental level rather than industrial scale, with a relatively small harvested area (10.8 ha). If the harvesting operation was conducted in a larger area, the trend might have been different for the processing costs due to increased in-woods distance, this was explored in the present study through sensitivity analysis but not field-tested. Extreme weather conditions, including snow storms and freezing temperatures, made harvest operation and field data collection difficult. This resulted in relatively fewer cycles being recorded for some of the operational phases (mainly extraction). Future research addressing the influence of climatic factors on harvesting productivity will be increasingly important as a changing climate alters winter conditions in northern climates.

## 3.6. Conclusion

The overall cost of operations was found to be 7.5% higher for the WT than Hyb TL. This was directly related to the extraction cost for WT being 15% higher than that of Hyb TL and may have been influenced by weather conditions during that phase of the operation. The cost of at-stump processing was comparable with the conventional at-landing processing. This suggests that Hyb TL may be a feasible approach in operations where protection of advance regeneration is critical, or where slash is left in the harvest unit for facilitating machine movement in stands with poor drainage and sensitive grounds. Though this practice can help in decreasing the cost for post-harvest soil remediation strategies and favors natural regeneration of the site, in-woods movement distance had a significant impact on the processing cost in Hyb TL. In addition, it is

likely that in-woods movement will decrease the machine life of the delimber, resulting in additional cost to the owner over the long-term. Outcomes of this study should be tested in industrial scale operations across arrange of harvest sizes and climatic factors before they are adopted in commercial forest operations.

## CONCLUSION

The primary aim of this study was to analyze and compare the costs and productivity of timber harvesting operations under different scenarios. Factors such as silviculture prescriptions and harvesting methods expected to influence the economic feasibility of a harvesting operation were evaluated. Best management practice (BMP) implementation is critical for sustainable timber harvesting practices as it reduces the severity of site disturbances occurring as an aftermath of mechanized harvesting. The cost of implementing BMPs in the region was quantified and found to be within an economically feasible range. The cost of BMP implementation was also compared with previous studies done across North America and the values obtained showed similar trends.

The first chapter of this thesis serves as introduction into the forests and forest industry of Maine. It discussed the measures of productivity and cost of operations. This portion of the study illustrated and detailed the various factors influencing productivity and costs of harvesting operations and analyzed the different studies conducted on BMP implementation and their important findings.

The second chapter of this thesis evaluated and compared the cost of a CC and a PH and discussed the major factors affecting the cost of harvesting operations. The cost of implementing BMPs incurred during the extraction phase was calculated for the different silvicultural treatments. The results of operational costs were in line with the general trend of CC operations being less expensive than PH, mostly because of the larger volume of merchantable timber produced in the CC. Extraction was the most expensive phase and contributed to about 52% and 70% of the total operating costs of CC and PH, respectively. Cost of BMP implementation was found to be directly influenced by the extent of poorly drained sensitive soils present. The pattern

of skid trails was also found to have an influence on the BMP costs. Even though total cost of extraction was influenced by BMP costs, it is evident from the results that BMP implementation can be incorporated into industrial-scale harvesting operations without considerably affecting the total harvesting cost.

The final chapter illustrated a comparison between a conventional whole-tree (WT) harvest and a hybrid tree-length (Hyb TL) method that is unique to the region. The study analyzed the operational aspects of at-stump processing of logs using a stroke-boom delimber and calculated the cost for implementing BMPs in the WT harvest. Total cost of operation was found to be higher for the WT than Hyb TL by 7.5%, which was a result of the higher extraction cost for WT. Therefore, it can be deduced that Hyb TL treatment can be executed without significantly altering the operational cost. Results from the study showed that costs of at-stump and at-landing processing of logs operations are comparable. However, in-woods movement distance was found to influence the at-stump processing costs. Hence, at-stump processing using a stroke-boom delimber can only be executed considering the extent of in-woods movement. Regarding BMP implementation costs, similar trends were generated as in chapter one. No specific endorsements can be made as the results may vary with increase in the extent of harvest area and climatic factors.

Insights and managerial impacts obtained from this study are expected to aid researchers, forest managers, loggers and other stakeholders of the region in efficient planning and execution of harvesting operation strategies as per their silvicultural requirements.



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Harikrishnan Soman was born in Kerala, India on June 28, 1991. He was raised in the town of Alleppey, Kerala, India and graduated from Sanathana Dharma Vidyasaala Higher Secondary School in Alleppey, India in 2009. Harikrishnan enrolled in College of Forestry, Kerala Agricultural University, India for pursuing his bachelor's degree in Forestry in 2010 and graduated in 2014. As a part of his undergraduate dissertation he worked on the "Reptiles of Neliyampathy Forest Range in Kerala, India". In 2014 after graduation, Harikrishnan worked as a research assistant at the College of Forestry in the Dendroclimatological studies of Teak. In 2017, Harikrishnan started working at the High Court of Kerala, India as an Administrative Assistant. After a short tenure, he joined the General Administration Department of Kerala, India where he worked under the same designation. In 2017, he was enrolled for Masters of Science in Forest Resources at the University of Maine where he is a graduate research assistant. His duties were to plan and execute field research for the Forest Operations lab.

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